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Improving the product development process of injection molded parts by utilization of additively manufactured molding tools

Master's thesis submitted in partial fulfillment of the requirements for the degree of Master of Science in Technology

Espoo, August 13th, 2017

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Abstract of master's thesis

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Title of thesis Improving the product development process of injection molded parts by utilization of additively manufactured molding tools

Degree programme Degree Programme in Mechanical Engineering

Major/minor Machine Design/Mechatronics **Code of professorship** K3001

Thesis supervisor Professor Jouni Partanen

Thesis advisor(s) Thomas Held, M.Sc. (Tech.)

Date 14.8.2017 **Number of pages** 89 **Language** English

Abstract

The purpose of this thesis is to study the potential of improving the product development process of injection molded parts by utilizing additively manufactured injection molding tools. The solution to achieve this goal is to produce injection molded prototypes for extensive testing early in the process before the production tools have been manufactured. By decreasing the risks of changes in the production mold and earlier certification tests, on the product that is being developed, helps to improve the overall lead time of the process.

The technical feasibility of using additively manufactured injection molding tools, both tools made out of plastic resin and metal powder, has been proved successful in academic research and industrial case studies.

In this study, the methods of utilizing additively manufactured injection molding tools were tested by designing a mold frame for testing tools manufactured out of different materials with different additive manufacturing methods. Three case studies were carried out, with a new part for each case. Technical feasibility of the tools as well as the benefits and limitations of utilizing them in the product development process were analyzed based on the results from these case studies. The theoretical part of the study was based on literature, scientific articles, journals and case studies.

The results show that additively manufactured injection molding tools can be beneficial in product development phases where testing of prototypes that are manufactured out of the final material and with injection molding is needed. The lead time of the process as well as the risks of changes to the production tools can be reduced by producing these kinds of prototypes early in the process.

Keywords Additive manufacturing, Rapid tooling, Prototyping, Injection Molding, Product Development

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Sammandrag av diplomarbetet

Författare Johnny Boxström		
Titel Förbättring av produktutvecklingsprocessen av formsprutade delar genom utnyttjande av additivt tillverkade formsprutsverktyg		
Utbildningsprogram Maskinteknik		
Huvud-/biämne Maskinkonstruktion/Mekatronik		**Kod** K3001
Övervakare Professor Jouni Partanen		
Handledare Diplomingenjör Thomas Held		
Datum 14.08.2017	**Sidantal** 89	**Språk** Engelska

Sammandrag

Målet med det här arbetet är att studera potentialen av att förbättra produktutvecklingsprocessen av formsprutade delar genom att utnyttja additivt tillverkade formsprutsverktyg. Lösningen till detta mål är att producera formsprutade prototyper för omfattande testning, i ett tidigt skede av utvecklingsprocessen, innan produktionsverktygen har tillverkats. Genom att minska på riskerna som är involverade i en ändring av produktionsverktyget samt genom tidigare certifieringstester, kan helhetsledtiden minskas för processen.

Den tekniska genomförbarheten av additivt tillverkade formsprutsverktyg, både tillverkade av plastharts och metallpulver, har bevisats i såväl akademiska undersökningar som i industriella fallstudier.

I den här studien testades metoder för utnyttjande av additivt tillverkade formsprutsverktyg genom att designa en formram för att testa additivt tillverkade verktyg av olika material och metoder. Tre fallstudier gjordes, med en ny del för varje studie. Den tekniska genomförbarheten av verktygen samt för- och nackdelar med att utnyttja dem analyserades på basis av resultaten från dessa fallstudier. Den teoretiska delen av studien baserar sig på litteratur, vetenskapliga artiklar, tidskrifter samt fallstudier.

Resultaten visar att additivt tillverkade formsprutsverktyg kan vara fördelaktiga i produktutvecklingsfaser där testning av prototyper kräver att delen är tillverkad av det slutliga materialet samt genom formsprutning. Ledtiden för helhetsprocessen samt riskerna med att ändra på produktionsverktyget kan minskas genom tillverkning av dessa prototyper i ett tidigt skede av produktutvecklingsprocessen.

Nyckelord Additiv tillverkning, Snabbtillverkning av verktyg, Prototyper, Formsprutning, Produktutveckling

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Diplomityön tiivistelmä

Tekijä Johnny Boxström		
Työn nimi Ruiskuvalutuotteiden tuotekehitysprosessin parantaminen hyödyntämällä ainetta lisäävällä valmistuksella valmistettuja ruiskuvalutyökaluja		
Koulutusohjelma Konetekniikan koulutusohjelma		
Pää-/sivuaine Koneensuunnittelu/Mekatroniikka		**Koodi** K3001
Työn valvoja Professori Jouni Partanen		
Työn ohjaaja(t) Diplomi-insinööri Thomas Held		
Päivämäärä 14.08.2017	**Sivumäärä** 89	**Kieli** Englanti

Tiivistelmä

Tämän diplomityön tarkoituksena on tutkia potentiaalia parantaa ruiskuvalutuotteiden tuotekehitysprosessia hyödyntämällä ainetta lisäävällä valmistuksella valmistettuja ruiskuvalutyökaluja. Ratkaisu tähän on tuottaa ruiskuvalettuja prototyyppejä laajaa testaamista varten tuotekehityksen varhaisissa vaiheissa, ennen kuin tuotantotyökaluja on valmistettu. Vähentämällä tuotantotyökalujen muutosten riskiä ja mahdollistamalla aikaisempaa sertifiointiprosessin aloittamista, tuotekehitysprosessin kokonaisläpimeno-aikaa voidaan lyhentää.

Ainetta lisäävällä valmistuksella valmistettujen ruiskuvalutyökalujen tekninen toteutettavuus, sekä muovista että metallista, on todistettu toimivaksi ratkaisuksi sekä akateemisissa että teollisissa tutkimuksissa.

Tässä työssä eri tapoja hyödyntää ainetta lisäävällä valmistuksella valmistettuja ruiskuvalutyökaluja testattiin suunnittelemalla muottirunko, jossa testattiin eri materiaaleista ja menetelmillä valmistettujen työkalujen toimivuutta. Suoritettiin kolme erillistä tapausta, joissa jokaisessa oli uusi muoviosa. Työkalujen tekninen toteutettavuus sekä niiden käyttämisen hyödyt ja rajoitteet analysoitiin edellä mainituista tapauksista saatujen tulosten pohjalta. Työn teoreettinen osio perustuu kirjallisuuden, tieteellisten artikkeleiden, tieteellisten lehtien sekä tapaustutkimuksien tarkasteluun.

Tulokset näyttävät, että ainetta lisäävällä valmistuksella valmistettujen ruiskuvalutyökalujen hyödyntäminen tuotekehitysprosessin vaiheissa joissa testaus vaatii prototyyppejä, joita on valmistettu ruiskuvalaamalla kappale lopullisesta materiaalista. Prosessin läpimenoaikaa sekä tuotantotyökalun muutostarpeen riskit voidaan vähentää tuottamalla tämän tyyppisiä prototyyppejä tuotekehitysprosessin aikaisissa vaiheissa.

Avainsanat Ainetta lisäävä valmistus, Työkalujen pikavalmistus, Prototyypit, Ruiskuvalu, Tuotekehitys

Acknowledgements

This thesis is done for ABB Wiring Accessories as a study to get more familiar with the additive manufacturing possibilities and how the product development process could be improved by utilizing additively manufactured injection molding tools.

My acknowledgments are directed to the thesis advisor Thomas Held for providing me with the opportunity to do my thesis at ABB Wiring Accessories on such an interesting topic. I would also like to thank Professor Jouni Partanen for functioning as the thesis supervisor and giving valuable support during the study.

For supporting the practical implementation, I would like to thank Juha Martikainen, Tuomas Teräsvuori, Olli Yli-Viikari, Teijo Lundberg and Marika Taipale from CM Tools Oy for assisting me with the injection molding part and Juha Teräväinen and Mikko Ojanto from Proto Labs for assisting me with the additive manufacturing. I would also like to thank everyone at ABB Wiring Accessories that has helped me with the study, especially by providing insight in the processes and by providing interesting products for the case studies. I sincerely hope that the results from this study provides ABB with knowledge for future research on the topic and a base for improving the product development process.

A special thank you goes to my family and friends who have supported me during the whole time of my studies.

Espoo, 13.8.2017

Johnny Boxström

Symbols

R_a	[µm]	surface roughness
T_{eject}	[°C]	ejection temperature
T_{melt}	[°C]	melt temperature
T_{wall}	[°C]	wall temperature
$t_{cooling}$	[°C]	cooling time
$t_{filling}$	[s]	filling time
v_{scan}	[mm/s]	scanning speed of laser light

Glossary and abbreviations

ABB	Asea Brown Boveri
ABS	Acrylonitrile-Butadiene-Styrene
AlSi10Mg	Aluminium alloy
AM	Additive Manufacturing
CAD	Computer Aided Design
CMS	Clever Mold System
DMLS	Direct Metal Laser Sintering
DSLS	Direct Selective Laser Sintering
IM	Injection Molding
IMSLS	Indirect Metal Selective Laser Sintering
MPa	Mega Pascal
PDP	Product Development Process
PA	Polyamide
PC	Polycarbonate
PE	Polyethylene
POM	Polyoxymethylene
PP	Polypropylene
PPO	Polyphenylene Oxide
PPS	Polyphenylene Sulfide
PS	Polystyrene
R&D	Research and Development
SL	Stereolithography
SLM	Selective Laser Melting
SLS	Selective Laser Sintering
WA	Wiring Accessories
Yb-fiber	Ytterbium-doped fiber

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1 Introduction

The product development process is a complex sum of activities, with a common goal of producing value for customers. The success of the process can be measured in how well the product developers have satisfied the needs of the customers, preferably before the competition. Lead time is therefore something worth improving during the product development process. At ABB Wiring Accessories improving the lead time for getting new products to the market is a continuous challenge. Most of the products that are being developed include injection molded plastic parts. These plastic parts need to fit together with other plastic, or metal, parts in different assemblies as well as they need to be possible to manufacture. The products also need to pass different standardized tests and certification processes. Due to the wide variety of parameters involved in developing these products, prototypes are being made during different development phases, to evaluate the performance of the parts. The most common method of producing these prototypes is to 3D print them, as this is a fast method for producing accurate prototypes. These 3D printed prototypes are good for visualization and even to some degree for functional testing. However, they cannot be used in standardized tests or for demanding functional testing. This means that crucial testing is usually done at later phases of the process when the production tools are already being manufactured.

To minimize the risk of part changes after the production tools have been made, a prototyping mold can be manufactured. These molds are traditionally made from a softer material, such as aluminium, as they don't need to withstand that much wear and aluminium is faster to machine than tool steel. Although the aluminium is faster to machine, the machining process is still quite slow, especially if changes are to be made to the part. The challenge of producing injection molded parts with a quick lead time can however be solved by utilizing additively manufactured injection molding tools.

Additively manufactured injection molding tools include the fast manufacturing cycles of 3D printing, while producing high quality injection molded parts for prototyping. This method has been proven in several case studies and due to its potential of improving the product development process, it is now studied in this thesis.

1.1 Research problem and scope

The purpose of the research is to study the feasibility of introducing injection molding into the earlier phases of the product development process (PDP) at ABB Wiring Accessories (WA). The approach taken was to use additively manufactured (AM) injection molding (IM) tools, to be able to produce prototypes and small product series with inferior quality and features than directly 3D printed prototypes, but with a more cost effective and faster process than with traditionally manufactured molding tools. The study also includes getting familiar with different AM processes and materials, suited for producing IM tools.

In addition, an evaluation of the needs for prototypes of different functions involved in the PDP was conducted. The main goal is to benchmark where in the PDP 3D printed prototypes are not sufficient enough and therefore where the studied approach of using AM IM tools would be of the greatest benefit.

1.2 Structure and implementation of the study

This master's thesis consists of a theoretical part and practical implementation. The theoretical part, presented in the beginning of the thesis, is based on literature study in the fields of product development, injection molding and additive manufacturing as well as studying previous research done with AM IM tools. The product development process is presented with a focus on the development phases where prototypes are mostly utilized, while still giving an overview of the entire process. The literature study of injection molding is divided into two segments; the injection molding machine and the injection molding process. Additive manufacturing methods covered in the literature study are methods that are commercially available and either suited for producing AM IM tools or for 3D printing prototypes. Also, the processes and knowledge at ABB WA, CM Tools and Proto Labs have served as additional background information for this study. The goal of the literature study was to set a base for the necessary knowledge needed to develop the PDP at ABB WA.

The practical implementation of the study was done as a case study divided into three different stages. The goal with this approach was to investigate different challenges and opportunities of using AM IM tools in the PDP. The implementation included designing of the IM tools, manufacturing of the tools from different materials using different AM methods and conducting injection molding test runs to produce small series of prototypes. The technical evaluation of the injection molding tools was done by measuring both the tools and the final injection molded parts with different measurement methods, conducting functional tests and analyzing the results to determine whether the proposed methods are feasible for implementation in the PDP.

In addition to the technical implementation, interviews were conducted to evaluate the current knowledge of using AM IM tools for prototyping and the state of using prototypes in the PDP. The interviews were done at ABB WA. Based on the results from the study, tools for improving the PDP by utilizing AM IM tools for prototyping is presented and at the end of the study conclusions and proposals for further research is made.

1.3 Constraints of the study

In this study, the focus is on evaluating the use of AM IM tools for use in product development, mainly for prototyping and small batches of production ready parts. The use of AM IM tools for final production is not included in this study. The practical implementation of the study is also limited to products from the installation materials portfolio at ABB WA, as the surface quality and dimension tolerances are not as strict for these products as for wiring accessories products.

The focus of this study is to evaluate the feasibility of using commercially available AM methods for producing AM IM tools to improve the product development process. Therefore, the IM process is presented on a general level in the theoretical part of the study, instead of concentrating on the details for achieving optimal IM conditions. The same approach has been taken for the literature studies of the PDP and AM. The PDP includes many stages with involvement of a vast amount of functions, which could all be analyzed for improvement. However, the goal in this study is to identify the areas where the AM IM tools could be used to improve the lead time of the PDP or to provide prototypes for specific testing of the products. This means that the literature study is restricted to the PDP phases and functions where prototypes are being utilized.

In the theory related to AM, the focus is on getting familiar with the commercially available AM technologies that could be used for producing AM IM tools. Although there are comprehensive guidelines for how to design for AM, these guidelines are addressed in this study, but not necessarily followed in the practical implementations, as the driving initiative is to study if similar results can be achieved by using AM IM tools as to using traditionally manufactured IM tools. Therefore, the post processing of the AM IM tools is kept to a minimum in the practical implementation. This should give an adequate level of indication whether it would be beneficial to utilize AM IM tools in the PDP at ABB WA instead of using traditionally manufactured IM tools for prototyping.

2 Stakeholders

In this chapter the main stakeholder, ABB Wiring Accessories is presented which is also for whom the study is done. Other central stakeholders involved in carrying out the study are briefly presented as well.

2.1 ABB Wiring Accessories

ABB Wiring Accessories is a business unit that produces installation materials and wiring accessories for residential and commercial buildings. The business unit in Finland is in Porvoo, and this unit is responsible for the entire market in the Nordic countries. The unit in Porvoo produces around 25 million products annually and employs around 100 employees. Product development is also located in the Porvoo business unit and most products developed include injection molded plastic parts.

Installation materials are a range of products that assists the wiring of a building. This includes, but is not limited to, mounting boxes, junction boxes, piping materials and covers. Most of the time, the installation materials are not visible in a building, except for covers. The installation materials are mainly used by the professionals carrying out the wiring of a building.

Wiring accessories are the electrification products that are visible and used by the end user. Products such as switches, socket outlets and signal lights as well as timers, thermostats and motion detectors are included in the wiring accessories portfolio. In addition to these products, ABB Wiring Accessories also provides home automation solutions and door entry systems.

2.2 Other stakeholders

CM Tools Oy

CM Tools Oy is a company located in Finland that provides services in production automation, tool manufacturing, maintenance and life-cycle service, machining and contract manufacturing. (CM Tools Oy, 2017) CM Tools Oy served as a provider of a turn-key solution for the utilization of additively manufactured (AM) injection molding (IM) tools. CM Tools Oy also provided insightful help on tool design and the injection molding process when analyzing the process in terms of self-sufficiency.

Proto Labs

Proto Labs is a provider of 3D printing services and an on-demand manufacturer of custom prototypes and low-volume production parts. The 3D printing services from Proto Labs were used to manufacture injection molding tools with Stereolithography and Direct Laser Metal Sintering technologies. Proto Labs was used in this study as a partner for producing the additively manufactured injection molding tools for the practical implementation.

3 Improving the product development process by utilizing additively manufactured injection molding tools

Most of the products produced at ABB WA involve thermoplastic parts, which are manufactured by injection molding. Therefore, the main goal in this study is to evaluate the feasibility of introducing injection molding as a part of the product development process in addition to other prototyping methods.

An overview of the product development process is introduced in chapter 3.1. The evaluation of the product development process and its different phases plays a big part in this study, especially the phases including different levels of prototyping and testing. As prototyping is a key topic in this study, it is also presented in this chapter. After a thorough presentation of the product development process based on literature and previous studies, the equivalent process at ABB WA is presented in chapter 3.2.

Another central part of this study is injection molding, which is presented in chapter 3.3. To gain a better understanding of the process, the chapter introduces the main components of the injection molding machine as well as the injection molding process itself. The design process of injection molded parts is also included, as it is a big part of the practical implementation of this study.

As stated, the focus in this thesis is to study the utilization of AM IM tools. Additive manufacturing is therefore presented in chapter 3.4, introducing the different technologies, materials and usage of the technology, with a focus on the methods and materials that are suited for producing AM IM tools. Previous research and literature studies on the utilization of AM IM tools is also included in this chapter.

3.1 The product development process

The generic product development process can be considered as a set of six phases, including planning, concept development, system-level design, detail design, testing and refinement and production ramp-up. From a design point of view the planning phase involves product platform and architecture ideation as well as the assessment of new technologies. This is also where the mission statement is developed. (Ulrich & Eppinger, 2012) However, as stated by Andreasen, Hansen & Cash (2015), the ideas are not valuable unless they can be developed to something that can be delivered. The first stage in making an idea into something valuable is the conceptualization of the idea.

Concept development is defined as a process where the form, function, and features of the product are developed. This includes developing industrial design concepts, building and testing experimental prototypes and evaluating the feasibility of the product concepts. (Ulrich & Eppinger, 2012) By proving the feasibility of a concept through prototypes, the original idea is getting further more valuable. An example provided by Andreasen, Hansen & Cash (2015) is patents. They state that a patent can be applied for without any proof of being possible to produce the product at the moment. However, once there is a proof of concept, the market value of the patent increases drastically. (Andreasen, et al., 2015)

In the system-level design phase the product architecture is developed, the product is divided into subsystems, the design is refined and the engineering design process is started. At the end of the system-level design phase, a geometric layout of the product and a specification of the subsystems of the product are defined. When the system-level design is finished, detail design is started. Detail design includes defining the actual part geometry and assigning functional tolerances to the product. This is also when materials are chosen. (Ulrich & Eppinger, 2012)

When the design phase has been completed, testing and refinement can be done. This is when the overall performance of the product is assessed, the regulatory approvals are obtained and necessary design changes are made. According to Ulrich & Eppinger (2012), testing of early prototypes should be done with parts that are made with the final geometry and materials similar to the intended materials for the final product, but not necessarily manufactured with the intended production processes. These prototypes are also known as alpha prototypes. The goal with testing the alpha prototypes is to determine that the product satisfies key customer needs and that the product works as intended. Later prototypes, known as beta prototypes, should be produced with the actual intended production method that has been decided for the end product. The intention of beta prototypes is to determine if there is a need to make some engineering changes to achieve the goals set for performance and reliability. (Ulrich & Eppinger, 2012)

As the product has reached a mature enough stage of design to be ready for production, production ramp-up can be started. The purpose of production ramp-up is to get the workforce familiar with the production of the new product and to eliminate any remaining problems in the production process. The ramp-up phase can also be used to test the product with super users to discover any remaining products flaws before the actual launch of the product. (Ulrich & Eppinger, 2012)

The process described above is a generic representation of the product development process (PDP). The PDP is however usually modified to suit the needs and specific situation that the company is facing. The adaptation of the generic process is therefore divided by Ulrich and Eppinger (2012) into different process types, based on the characteristics of the products. These process types are described as:

- Generic products
- Technology-push products
- Platform products
- Process-intensive products
- Customized products
- High-risk products
- Quick-build products
- Complex systems

The PDP of generic products, also known as market-pull products, is following the generic process described earlier in this chapter. The process is usually driven mainly by a market opportunity, and the most suitable manufacturing processes are chosen to produce the products. Another category of products, which can be described as the opposite to market-pull products, is products that are described by Ulrich and Eppinger (2012) as technology-push products. (Ulrich & Eppinger, 2012)

The technology-push products are characterized by the development of a completely new technology which is then applied to different products in different markets. Ulrich and Eppinger (2012) presents Gore-Tex as an example of a successful technology-push product.

The Gore-Tex technology has been implemented in a vast variety of products, ranging from clothes to high-performance electric cables.

The development of a new product can however be driven by an already existing product. These products are known as platform products, which are quite similar to technology-push products, but are differentiated by the fact that the technology is already existing in the market and the development of a platform product is expected to be successful based on the proven success of the preexisting technology platform. The use of platform products can greatly reduce the manufacturing costs of products as well as the time-to-market. (Ulrich & Eppinger, 2012; Meyer, 1997)

Products can also be characterized by the manufacturing process. Process-intensive products is a category described by Ulrich & Eppinger (2012) as products where the manufacturing process plays a key role in the whole PDP of the product. The process-intensive products are usually products that are produced in very high quantities, such as paper, semiconductors or different plastic products. When it comes to producing large quantities of a product, injection molding is a widely used manufacturing process. (Ulrich & Eppinger, 2012; Kazmer, 2007)

When designing a product for IM, a big part of the process is acquiring the injection mold. The quoting of the mold needs to be done, as it will be a big investment and therefore a considerable impact on evaluating the business case. The next stage concerning the mold in the PDP for IM products is mold design. In conjunction of designing the end product, the manufacturing tools also need to be designed. When the mold and product designs are ready, the mold needs to be manufactured, tested and improved. The added effort on the overall PDP when designing a product for IM is visualized in figure 1. (Kazmer, 2007)

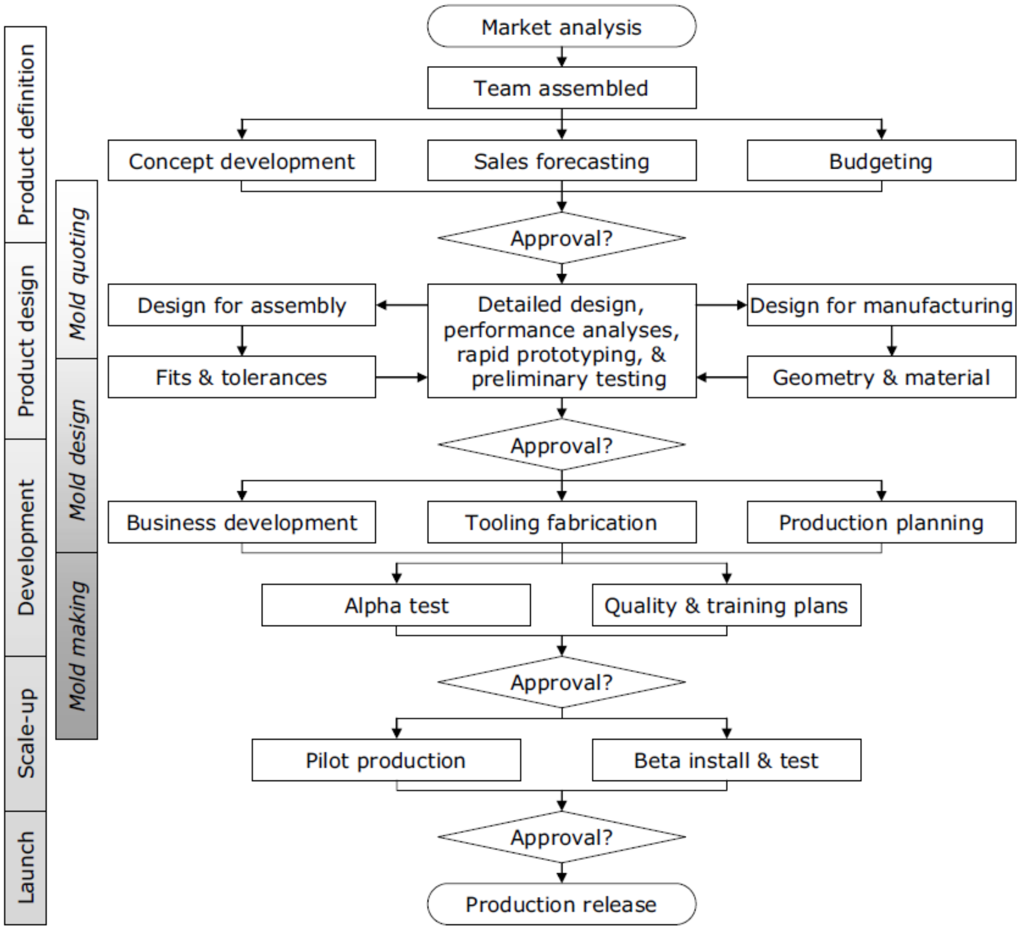


Figure 1. A visualization of the PDP of IM products (Kazmer, 2007)

The next category of products presented by Ulrich & Eppinger (2012) is the customized products. Customized products can be identified by the presence of variations of a standard product design. Products like switches or motors can have one basic design which can then be altered to suit the specific needs of the customer. The PDP of customized products is usually very well documented and the development process can to some degree be automated for new variations of the product. (Ulrich & Eppinger, 2012)

High-risk products are a category of products where the risks, be it technological or market risks, are substantially high. The process is driven by continuously evaluating and reducing the risks. Management of risks such as customer acceptance and technical details can be done by using prototypes for testing early in the development process. A process relying on building and testing different prototypes quickly in multiple cycles, is called quick-build products. (Ulrich & Eppinger, 2012)

Quick-build products is based on sorting the different parts and features of the product in order based on priority. Several iteration cycles are conducted and prototypes are built and tested in each iteration and it is not unusual to even have the customer involved in some testing. The product is then modified in the next iteration based on the results and the next prototyping and testing cycle is done. The process stops when either the time or the budget runs out. (Ulrich & Eppinger, 2012)

The last category of PDP presented in this chapter is called complex systems by Ulrich and Eppinger (2012). Complex systems are identified by large-scale products with many components. A noticeable difference between the generic PDP and complex systems PDP is that the product in the complex systems PDP is divided into smaller parts and different teams will then develop each part. Another team is then responsible of integrating the different parts into the product. Examples of complex systems products are cars and airplanes. (Ulrich & Eppinger, 2012)

The characterization of the PDP is a tool used in this study to help identify where the process can be improved. The PDP at ABB WA is studied in the next chapter. By identifying the characteristics of the products at ABB WA as well as the need and utilization of prototypes during the PDP, case studies can be conducted to evaluate the feasibility and need of using AM IM tools for prototyping.

Prototyping

Ulrich & Eppinger (2012) defines a prototype as "an approximation of the product along one or more dimensions of interests". According to this definition, it can be concluded that before producing a prototype, a plan should be made for what is to be achieved through the prototype. Prototypes can be used for several different tasks, during different phases of the PDP. A prototype can be used for communication, both internally throughout the company as well as for communicating ideas or features to the customers. By producing prototypes early in the process, the marketing department can reduce the uncertainty of the customer needs by involving real customers in the process. However, prototypes made early in the development process are usually incomplete, because all features are not known or the equipment for manufacturing high fidelity prototypes are not available, which can lead to bad feedback from the customers. Therefore, it is beneficial to include different customers at different stages of the PDP, ranging from requesting customer to launching customer, reference customer, first buyer and lead user. (Ulrich & Eppinger, 2012; Thomke & Bell, 2001; Enkel, et al., 2005) A visualization of customer involvement in the PDP can be seen in figure 2.

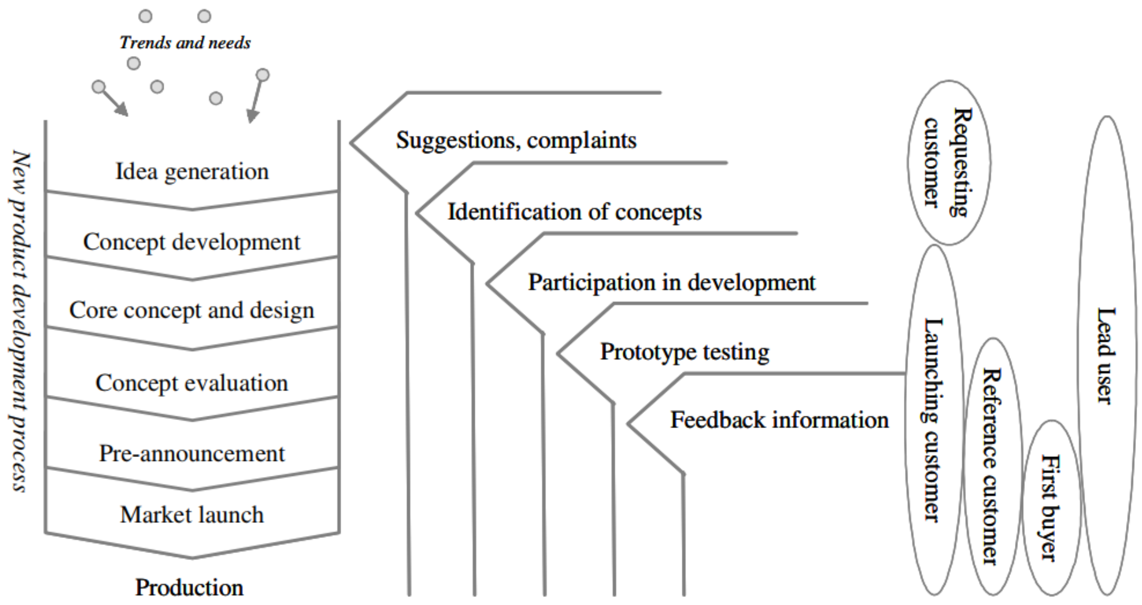


Figure 2. A visualization of customer involvement in the PDP and types of feedback from different types of customers. (Enkel, et al., 2005)

Another usage for prototypes is called integration. This is where prototypes are used to validate whether the developed component will interact with the other components as planned. The prototypes that are used for integration testing, are usually built at different maturity levels of the PDP. This way, the impact of the developed component can be controlled and improved throughout the entire process, without the risk of non-working assemblies. The use of these prototypes can also help in the design decision making process. (Ulrich & Eppinger, 2012)

Producing prototypes may also reduce the risk of having to make changes after expensive stages in the process, such as when a production tool has already been manufactured. By utilizing prototypes to evaluate the products, the success probability can be increased substantially, as the iterations can be done more quickly and the fit of the parts can be evaluated before the production tools have been manufactured. (Ulrich & Eppinger, 2012) A schematic of the success probability for a conventional iteration process vs. a process where prototypes are utilized is presented in figure 3.

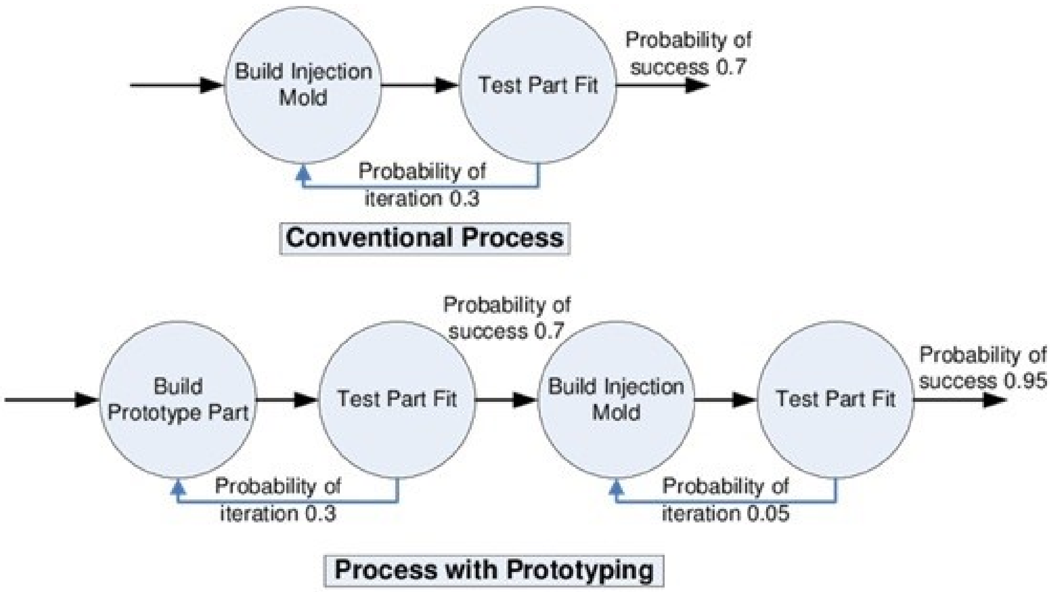


Figure 3. Schematic of success probability based on iteration process. (Ulrich & Eppinger, 2012)

Although there are clear benefits of using prototypes in the PDP, there are also risks involved. One of these risks is that prototypes that do not contribute to the product development process are produced. To avoid this risk, a plan for the needs that each prototype should satisfy should be made. (Ulrich & Eppinger, 2012)

Ulrich & Eppinger (2012) suggests a four-step method for planning the prototyping process. This method consists of:

- Defining the purpose of the prototype
- Deciding the level of approximation of the prototype
- Making an experimental plan
- Setting up a schedule for producing and testing the prototypes

By clearly stating the purpose of the different prototypes, controlling the prototyping process becomes easier. Deciding the level of approximation of the prototype makes it possible to concentrate the effort of getting the intended information from the prototype, while not spending extra time on details that does not contribute to the goals. At this step the decision on what type of prototypes is to be made, if it should be an analytical prototype or a physical prototype, is done. The experimental plan should include the variables that are involved in the testing of the prototype, the measurements that should be performed and the methods used for analyzing the results. To be able to allocate the needed resources and keep track of the overall progress of the PDP, the schedule should be made for the different tasks included in the prototyping process. (Ulrich & Eppinger, 2012)

Successful product development

The level of success of a product development process can be described as how well the new product provides meaningfully unique benefits. As suggested by Sethi, Smith & Park (2001), these benefits can best be reached by involving different functions of the company in the process, such as marketing, engineering, manufacturing and purchasing. By including these functions at different phases of the PDP, it is more likely that a greater variety of mature ideas will be generated as members of a certain function tend to overlook details that are linked to the other functions in the company. (Sethi, et al., 2001)

Although the involvement of different functions inside the company is beneficial, it can also be beneficial to include third parties in the PDP, also known as taper integration. By outsourcing some of the PDP, the company can get familiar with new technologies as well as benefit from effective usage of resources. Rothamel, Hitt & Jobe (2006), uses Dell as an example for taper integration. At Dell it is a common practice to outsource design activities to a company called Flextronics, while concentrating on developing the product components in-house. (Rothamel, et al., 2006)

When a lot of different functions in a company and third-parties get involved in the product development process, the demand for good management of the process increases. One successful model for managing product development projects is the so-called stage-gate system. The stage-gate system functions as a blueprint for the project, incorporating and organizing all the necessary product development phases, to make the process as effective as possible. During the process the gates function as checkpoints for specified deliverables, while the stages in between the gates function as the guidelines for achieving the goals set for the next gate. When the work has been finished during a stage, a gate meeting is set up, so that managers can assess whether the set goals have been achieved, and action can be taken if it is recognized that the process is not going according to the initial plan. (Cooper, 1990) A schematic of the stage-gate system can be seen in figure 4.

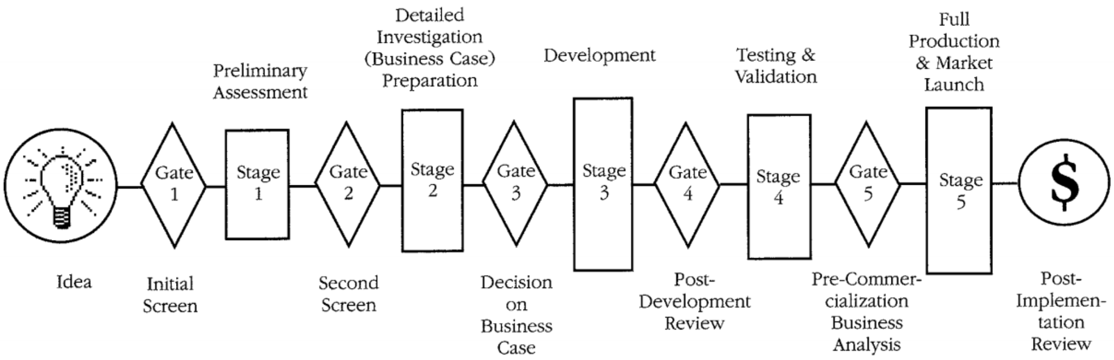


Figure 4. Schematic of the stage-gate system. (Cooper, 1990)

One of the strengths of the stage-gate system is that development processes can be managed and processed in parallel. By utilizing different functions of the company at the same time, the lead time for the overall PDP can be reduced and the input to the process is more likely to be of a multidisciplinary nature, reducing the risks of overlooking important features. (Cooper, 1990) However, as concluded by Sethi & Izbal (2008), the stage-gate system can also have a negative effect on the PDP. When the gate questions are strict, objective and frequently applied in the process, the PDP becomes inflexible. An inflexible PDP increases the risk of learning failure for the product development team. (Sethi & Iqbal, 2008)

3.2 Product development at ABB Wiring Accessories

To be able to conduct a study of improving the PDP of injection molded products at ABB WA by utilizing AM IM tools, the characteristics of the current PDP needed to be established. The characterization was done based on comparing the literature study of the PDP to the processes at ABB WA. Information about the processes at ABB WA as well as the product types, was gathered through interviews of members of the product development team and by studying the product portfolios at ABB WA.

Product portfolios

As there are over 400 products in the portfolio at ABB WA, containing thousands of different parts, there is also a wide variety of different types of products. In fact, almost every category described in chapter 3.1 can be identified in the product portfolio at ABB WA, except for technology push products. Different products from the portfolio, categorized by their type of product from a PDP point of view can be seen in table 1. High risk products and quick-build products are excluded from the table, as although the equivalent processes are sometimes present at ABB WA, they cannot be linked to specific products in the portfolio.

Category	Product	Description
Generic products	 Conduit bends	The conduit bend is used as protection for electrical cables, and these products can therefore be seen as a product that is fulfilling a market need, i.e. a generic product.
Technology-push products	N/A	N/A
Platform products	 Socket outlets	The socket outlet is based on a common platform, which is the socket itself, however there can be different products based on that platform. Therefore, the socket outlets can be categorized as platform products.
Process-intensive products	 Most of the products at ABB WA	Most of the products at ABB WA have plastic parts manufactured by injection molding, therefore most products are categorized as process-intensive products.

Customized products	 Light switches	The light switches share the same basic components, but can vary in amount of switch rockers as well as in connector setups. Therefore, the light switches can be categorized as customized products.
Complex systems	 ABB i-bus KNX	The KNX systems can be seen as complex systems as many different devices and parts, developed by different teams, are needed for the entire system to work.

Table 1. Examples of products in ABB WA portfolio categorized based on type of products. (ABB Wiring Accessories, 2017)

Current processes

As described in the section above, categorization based on analyzing the product portfolio can be done, to help identifying the most suitable PDP implementation. However, the processes are often modified based on the situation and the people involved in the project. Based on discussions with the staff and by examining earlier studies done at ABB WA, it can be concluded that most of the product development processes can be categorized to mainly be a combination of the platform products, process-intensive products and quick-build products processes described in chapter 3.1. There are also strict regulations that wiring products need to follow, such as the SFS 6000 standard for low voltage installations. Due to the standards and certification requirements, different tests need to be conducted on the products during the PDP. (ABB Wiring Accessories, 2016-2017; Luomi, 2014)

The current PDP at ABB WA follows the stage-gate model. A generic representation of the stage-gate model, with the focus on the stages where AM IM tools could be beneficial, is presented in chapter 4.4.

Conclusion

Most of the products produced by ABB WA are high volume products that mainly consists of thermoplastic parts. This leads to the products being process-intensive by the fact that most of the parts included in the products are plastic parts produced by injection molding.

There are strict specifications and regulations that dictates how buildings should be wired and how products that are operated by electricity should be designed. The products in the portfolio of ABB WA rely on these standards and regulations, and the PDP is therefore highly affected by these, and different tests needs to be conducted for the products to be certified.

Because the products are fairly small in size and mostly made out of a thermoplastic, they can quickly and easily be tested by producing rapid prototypes. This opportunity is utilized at ABB WA and thus the product development process can also be identified as being quick-build products. However, the prototypes used now are mostly 3D printed parts, which cannot be used to test some of the requirements set by the standards.

3.3 Injection molding

The injection molding process is defined as a cyclic manufacturing process for producing identical parts. The process also enables the production of these identical parts with high dimensional accuracy as well as a relatively short cycle time. IM is therefore the most common manufacturing process used for producing high volumes of plastic products. While IM enables fast production of identical products, the costs and lead time for the PDP of IM products are high. The complex machines needed for the IM process are a big investment, but fortunately the same IM machine can be used for different molds to produce several different products. However, the molds are usually manufactured with time consuming machining processes, are also expensive. Therefore, the PDP of the IM products need careful planning. Mistakes that are not identified before the mold has been manufactured, can delay the process by up to several months. To ensure that the mold is according to the specifications, test runs and improvements are made before the mold is taken into production. The testing and modification processes further prolongs the lead time for producing injection molds. (Zheng, et al., 2011; Barkoula, et al., 2010; Kazmer, 2007)

3.3.1 The injection molding machine

The injection molding machine mainly consists of two units. These are the injection unit and the clamping unit. The injection unit is further divided into the hopper, the rotating screw and a heated barrel. Included in the injection unit is also the process controller, hydraulic power supply, the injection cylinder. The main components of the clamping unit consist of the clamping cylinder, tie rods, a moving platen, the mold and a stationary platen. A separate tempering system is also usually used to cool down the mold during the molding process. (Zheng, et al., 2011; Kazmer, 2007) Schematics of the IM machine can be seen in figure 5.

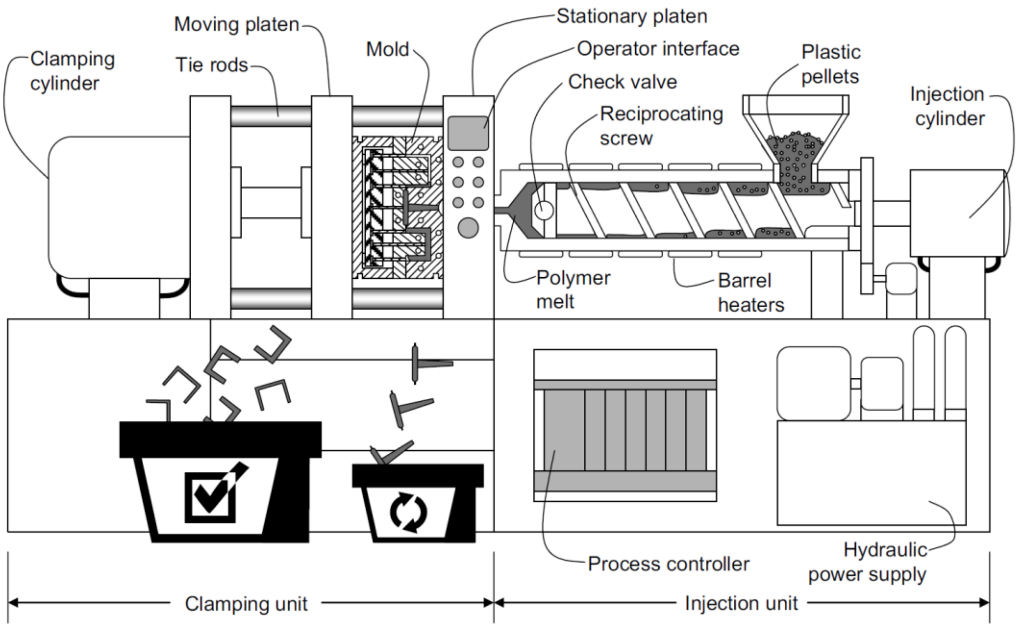


Figure 5. A representation of the injection molding machine (Kazmer, 2007)

The most central part of the injection molding machine is however, the injection unit. The injection unit consists of the hopper, that contains the plastic granules that are fed into the barrel, a rotating screw, that feeds the granules inside the barrel towards the mold, a heated barrel that melts the granules and serves as a housing for the melted plastic until it is finally injected into the mold which creates the final shape of the part. (Lindner & Unger, 2002) The injection unit can be seen in figure 6.

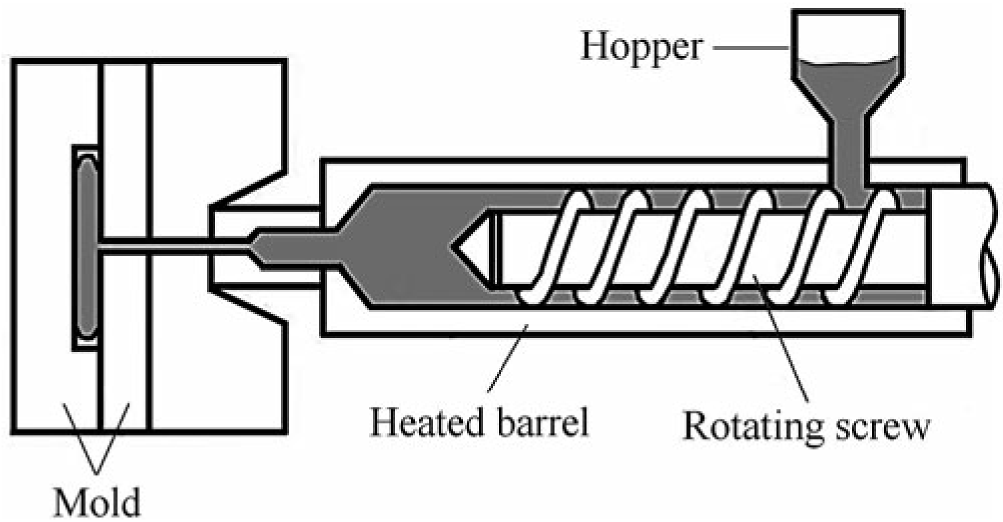


Figure 6. A representation of the injection unit including the hopper, rotating screw and the heated barrel. (Lindner & Unger, 2002)

The injection mold

When designing a product that will be manufactured by IM, a variety of different aspects need to be considered. As in the PDP of IM products described by Kazmer (2007), the planning of the mold starts already in the product definition phase. This is done because the expected production volumes will determine whether the mold will have a single cavity or multiple cavities. As the number of cavities increase, the amount of material that is injected into the mold per cycle also increases, which in turn places a higher demand on the IM machine. (Lindner & Unger, 2002)

When the number of cavities have been decided, the type of the mold is decided next. The mold can either be a two-plate mold or a three-plate mold, of which the two-plate mold is the more common type. Next, the choice of sprue, the placement of the cavities in the mold and the type of gating is specified. (Lindner & Unger, 2002)

Due to the high temperature changes involved in the IM process, a temperature control system needs to be designed, as the temperature control has a big impact on both the quality of the produced part as well as on the cycle time. Therefore, the main objective of the temperature control system is to maximize the heat transfer, which lowers the overall cycle time, while maintaining a uniform wall temperature, which minimises the uneven shrinkage and warpage of the parts. (Lindner & Unger, 2002; Kazmer, 2007)

The type of ejection system is decided next, typically ejection pins or stripper rings are chosen. When the ejection is planned, the venting of the mold is inspected. In case the venting through e.g. ejector pin holes, venting channels can be added to the mold plates to provide sufficient venting. (Lindner & Unger, 2002) A representation of the ejection system can be seen in figure 7.

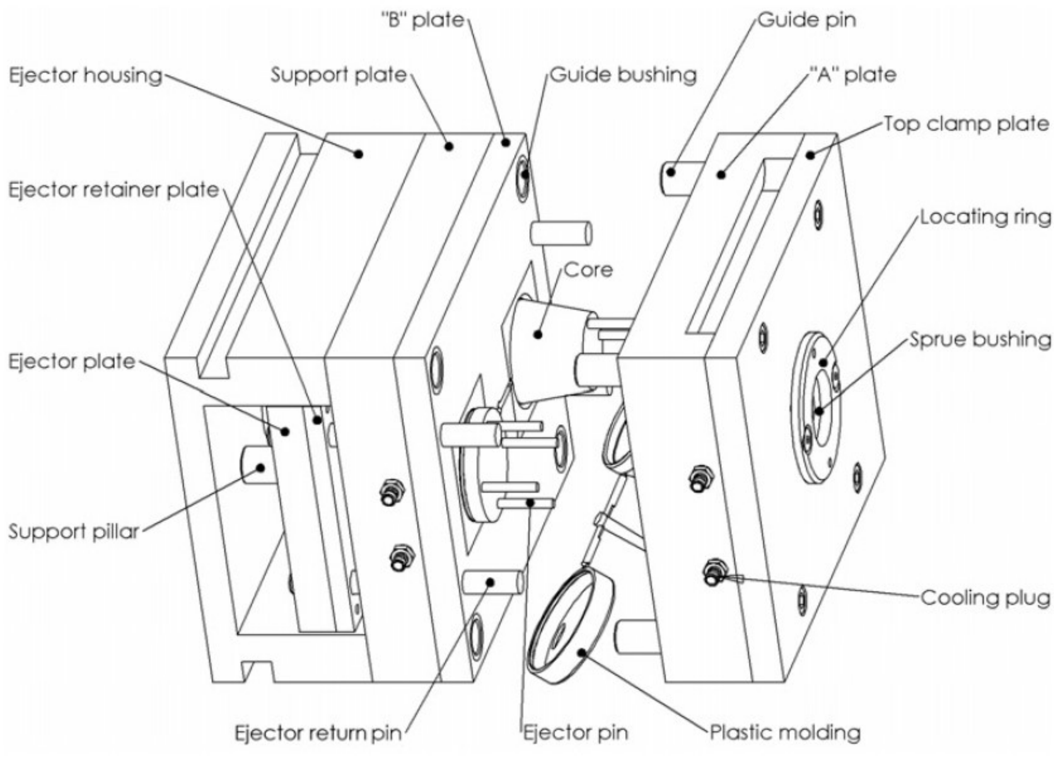


Figure 7. Part ejection from the injection mold by ejection pins. (Kazmer, 2007)

Next in the process, the materials for the mold parts are specified, to meet the specifications of the IM process. The main features that are sought of the material used in molds are; high wear resistance, high corrosion resistance, good dimensional stability and good thermal conductivity. Most common materials used for production molds are case-hardening steels, heat-treatable steels, through-hardening steels, corrosion resistant steels or sometimes also aluminium alloys. Through-hardening steels are used for molds that are subjected to abrasive plastics during the IM process, such as glass fibre filled plastics. Corrosion-resistant steels are used for injection molding of parts that involve corrosive plastics or additives. The surface of a mold can also be treated with different surface treatment methods, to achieve certain qualities, including surface hardness, compressive strength, wear resistance, corrosion resistance, sliding properties or de-molding. (Lindner & Unger, 2002)

When choosing the material for the mold, it is usually a balance between strength of the material and the heat transfer ability of the material. When choosing a material for a mold, the most important strength characteristic is the fatigue limit stress, which describes the materials ability to endure cyclic stress, with a theoretically infinite number of cycles, applied to the material without material failure. For most steels, the fatigue limit stress is approximately 50% of the yield stress of the material. (Kazmer, 2007)

When all of the stages mentioned above have been completed, the design process can be started, after the shrinkage of the material used for the product has been anticipated. The factors involved in the shrinkage of the part are the thermal contraction of the plastic, the compressibility of the plastic and the thermal expansion of the mold. The thermal expansion of the mold is however, in most cases very minimal. As it is the coefficient of thermal of the mold material multiplied by the difference in temperature between the mold coolant and room temperature, the expansion of a mold made from P20 mold steel and used for ABS plastic molding, is only around 0.05%. Although this is a comparatively small change in dimensions, it should be considered when designing molds for parts with tight tolerances. A much larger impact on the shrinkage of the part comes from the thermal contraction of the melted plastic as it cools down after it has been injected into the mold. A common tolerance for shrinking in commercial products, is specified as ± 0.4%. (Lindner & Unger, 2002; Kazmer, 2007)

A flow chart of the entire design process described above can be seen in figure 8.

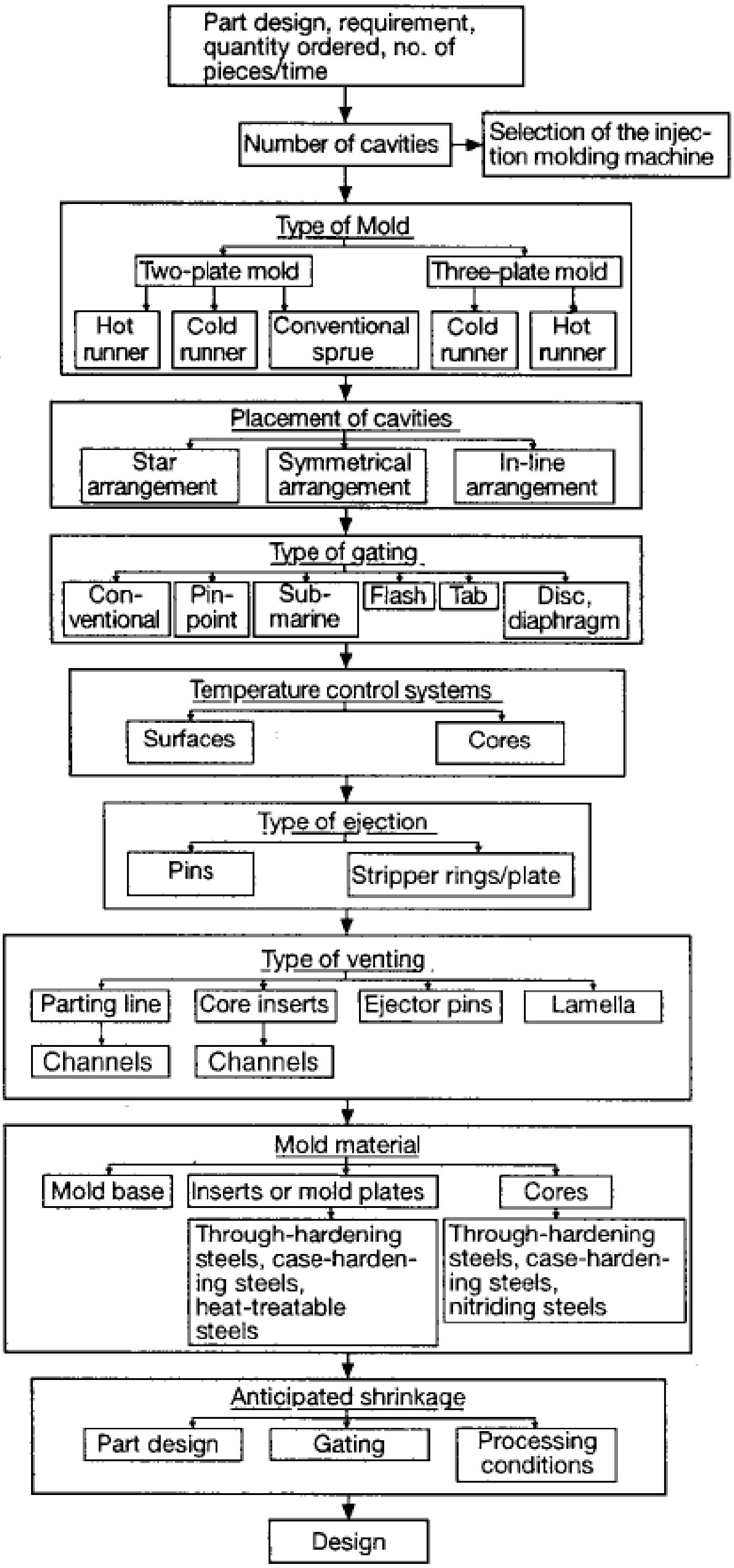


Figure 8. A flow chart for designing injection mold systems (Lindner & Unger, 2002)

3.3.2 Injection molding process

To understand the different parameters that are involved in injection molding, the process itself needs to be examined, in addition to examining the molding machine and injection mold that were introduced in section 3.3.1. The injection molding process involves many different stages, which adds up the different parameters that needs to be controlled, to achieve a successful IM process. The stages and parameters are described below.

When beginning the IM process, the mold is closed with a certain force, called clamp tonnage, which is specified by the integral of the melt pressure that is acting on the projected area of the mold cavities. The projected area is used to calculate the clamp tonnage because the pressure on walls inclined in comparison to the opening direction of the mold have very little impact on the force needed to keep the mold closed. (Kazmer, 2007)

Plastic granules are stored in the hopper, which feeds them into the heated barrel. The granules are then transported forward towards the mold. Due to friction and heat generated by heating elements in the barrel, the granules melt and are transported further down the barrel until it reaches the nozzle. At this stage the nozzle is closed, so the molten plastic that is being forced against it by the screw, builds up a pressure. When the pressure starts building up, the screw moves backwards to allow for a specified volume of plastic to be stored between the end of the screw and the nozzle. As the specified volume of plastic for the process has been reached, the screw stops rotating. Now the nozzle is opened and the screw is moved toward the nozzle, forcing the molten plastic into the mold. This is known as the filling process. (Lindner & Unger, 2002)

During the filling process, the molten plastic is injected into the mold at a certain pressure, known as the filling pressure. This pressure has a big impact on the overall IM process. If the filling pressure is high then there will be an increased need of clamp tonnage, which is the measurement of the force needed to keep the mold closed during the IM process. Also, a higher risk of pressure drop in the feed system as well as elevated risk of running out of machine capacity in case of miscalculations are results of a high filling pressure. Therefore, the typical filling pressure is suggested to be less than 100 MPa during the IM process. The filling pressure is a function of the wall thickness, which means that with a decreased wall thickness the filling pressure rises. The filling pressure can further be modified by adjusting the melt temperature, as the filling pressure drops with an increased melt temperature. (Kazmer, 2007) The results from the analysis of minimum wall thickness compared to the filling pressure for an ABS part with a melt temperature of 239°C is presented in figure 9.

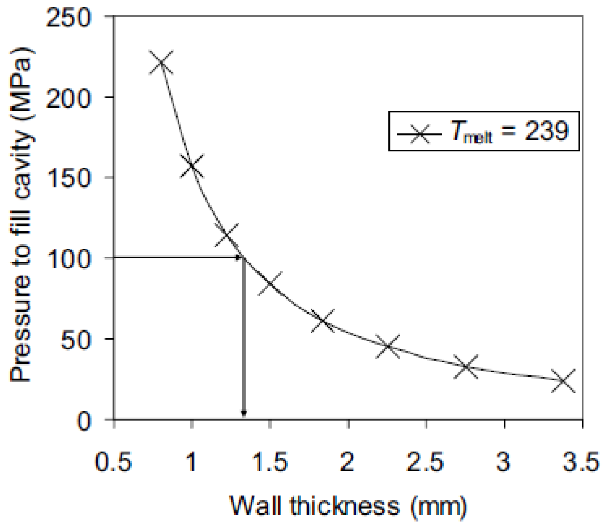


Figure 9. The minimum wall thickness has been analyzed for ABS material at a melt temperature of 239°C and a maximum filling pressure of 100MPa. The minimum wall thickness is 1.36mm. (Kazmer, 2007)

After the mold has been completely filled with plastic, the screw is either held at its position or moved a small amount towards the nozzle, to maintain a holding pressure. This phase is called the packing or holding phase. It is meant to compensate for the shrinkage of the plastic part, which takes place as the thermoplastic polymer cools down. The packing pressure is usually around 50 to 90% of the injection pressure. However, the exact packing pressure is not known until the mold is operated and the molding process parameters and shrinkage control is set. (Kazmer, 2007)

Before the screw can move backwards in the barrel, the molded part must be cooled down further, until the gates have completely solidified. When the part has cooled down enough, the mold can be opened and the part can be ejected from the mold. (Lindner & Unger, 2002)

As there are many different phases involved in the IM process, it is advised that simulations and analysis is made prior to investing in the tools, to ensure the best possible performance. A common analysis made when designing IM parts is mold filling analysis. By performing mold filling analysis, the designer can ensure that the intended part will be completely filled with the intended material for the part and the IM machine that will be used. The mold filling analysis can also be used for analyzing the mold pressures, which can indicate the overall performance of the mold process, as well as the melt front advancement in the cavity of the mold. The melt front advancement analysis can be used to predict problematic areas of the part, such as melt front stagnation. Melt front stagnation can lead to rising melt pressure, which in turn can lead to a higher clamp tonnage or flashing. Flashing is the phenomenon where the injected plastic forces itself in the gap between the mold plates, resulting in unintended geometry. Melt front stagnation can also lead to other unwanted defects, such as unfilled areas of the mold and warpage due to high residual stress. (Kazmer, 2007) A more comprehensive list of errors that can arise due to bad mold design is presented in table 2.

Faults	Possible problems
Wrong location of gates	Cold weld lines, flow lines, jetting, air entrapment, venting problems, warpage, stress concentrations, voids and/or sink marks
Gates and/or runners too narrow	Short shots, plastics overheated, premature freezing of runners, sink marks and or voids
Runners too large	Longer molding cycles and waste of plastics
Unbalanced cavity layout in multiple cavity mold	Unbalanced pressure buildup in mold, mold distortion, dimensional variation between products (poor shrinkage control), poor mold release, flash and stresses
Non-uniform mold cooling	Longer molding cycle, high after-shrinkage, stresses (warpage), poor mold release, irregular surface finish, distortion of part during ejection
Inadequate provision for cavity air venting	Need for higher injection pressure, burned plastic (brown streaks), poor mold release, short shots and flow lines
Poor or no air injection	Poor mold release for large parts, part distortion and higher ejection force
Poor ejector system or bad location of ejectors	Poor mold release, distortion or damage in molding and upsets in molding cycles
Sprue insufficiently tapered	Poor mold release, higher injection pressure and mold wear
Sprue too long	Poor mold release, pressure losses, longer molding cycle and premature freezing of sprue
No round edge at the end of sprue	Notch sensitivity (cracks, bubbles etc.) and stress concentrations
Bad alignment and locking of cores and other mold components	Distortion of components, air entrapment, dimensional variation, uneven stresses and poor mold release
Mold movement due to insufficient mold support	Part flashes, dimensional variations, poor mold release and pressure losses
Radius of sprue bushing too small	Plastic leakage, poor mold release and pressure losses
Mold and injection cylinder out of alignment	Poor mold release, plastic leakage, cylinder pushed back and pressure losses

Table 2. Examples of errors in mold design (Zhou, 2013)

Injection molded part design

In addition to the errors in mold design, design rules of the molded part need to be followed, to achieve a stable IM process and high-quality parts. The basic rules of IM molded part design, according to Mennig & Stoeckhert (2012) are:

- The gates, and weld lines, should be positioned away from both areas of the part that are affected by high stresses and from the edges of the part.
- Uniform wall thicknesses are recommended and when not possible to have completely uniform wall thicknesses, the wall thickness should change gradually
- Wall thicknesses should be kept as small as possible, while still thick enough to ensure a feasible IM process
- Optimized wall thickness, to ensure a uniform flow front
- Mass concentrations should be avoided, if they cannot be avoided they should be placed as close to the gates as possible
- Sharp inside edges should be avoided
- Simplified designs if possible, as it decreases the need of slides for undercuts

3.4 Additive manufacturing

As mentioned in previous sections, additive manufacturing plays a key role in this study. The focus is on evaluating the technology for producing injection molding tools, also known as rapid tooling, but also to compare injection molded products to additively manufactured prototypes.

A general overview of additive manufacturing and different usage areas of the technology is presented in Chapter 3.4.1. Included in this chapter is also an introduction of the most common commercially available technologies used for rapid prototyping and rapid tooling.

In chapter 3.4.2 the focus is on design opportunities and limitations for additive manufacturing, especially focusing on producing prototypes for different product development phases and for rapid tool design.

3.4.1 Overview of additive manufacturing

Additive manufacturing was first developed for quickly producing physical prototypes from a digital model. In the early stages of AM, the prototypes were used mainly for visualization of the products that were developed. The usage of the technology has however expanded to other purposes as the technologies have developed. With increased accuracy and quality of the AM parts as well as the addition of new materials, the usage of the prototypes could be expanded to include functional and assembly testing. The technology has developed so far that it can in some cases even be used for end-products. (Gibson, 2015)

Additive manufacturing is a method of producing physical parts and there are quite a few technologies that are utilized for the method. Gibson (2015) divides the technologies used in additive manufacturing into the following main categories:

- Liquid polymer systems
- Discrete particle systems
- Molten material systems
- Solid sheet systems
- Metal systems

- Hybrid systems

Parts made with different AM technologies can be seen in figure 10, where part a. is made with stereolithography (SL), while b. and c. are produced with material jetting technology and these are both liquid polymer systems. Part d. is manufactured with a metal powder bed fusion machine, which is part of the metal systems category, part e. is produced with a sheet lamination machine with ink-jet printing capability and parts f. and g. were produced with fused deposition modeling technology, categorized as a molten material system. Parts h. and i. are manufactured with selective laser sintering (SLS), which is a discrete particle system. (Gibson, 2015)

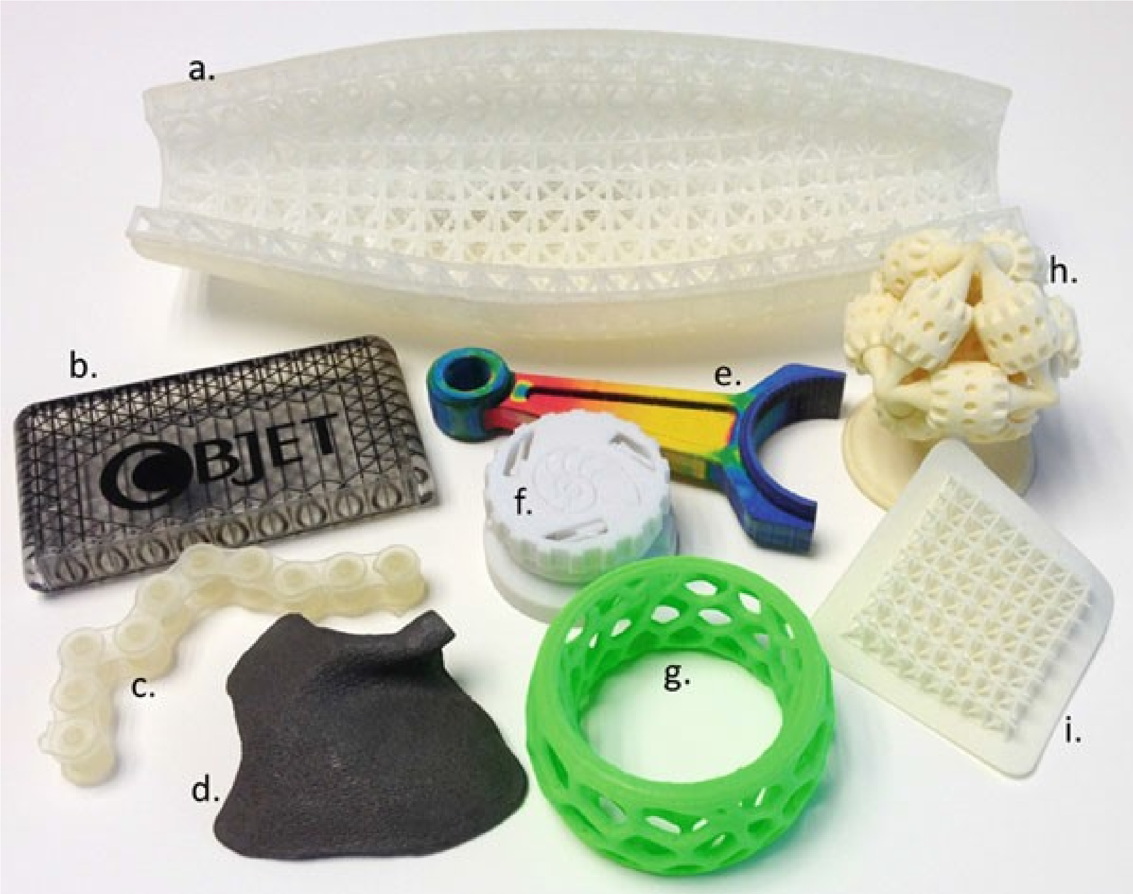


Figure 10. Parts made with different AM technologies and materials. (Gibson, 2015)

One of the most commonly used technologies in additive manufacturing is liquid polymer systems. The first liquid polymer system that was commercialized was the SL technology introduced by 3D Systems. The technology relies on a liquid photopolymer that is cured using an UV light. The photopolymer is contained in a reservoir which has a movable platform on which the part is built. The platform starts at the surface of the photopolymer and moves downwards as the laser cures the photopolymer layer by layer. The layers are cured by a laser beam that scans the surface of the polymer according to the information acquired from the 3D CAD model. The operation principle of the SL method is demonstrated in figure 11. (Gibson, 2015; Poprawe, 2011)

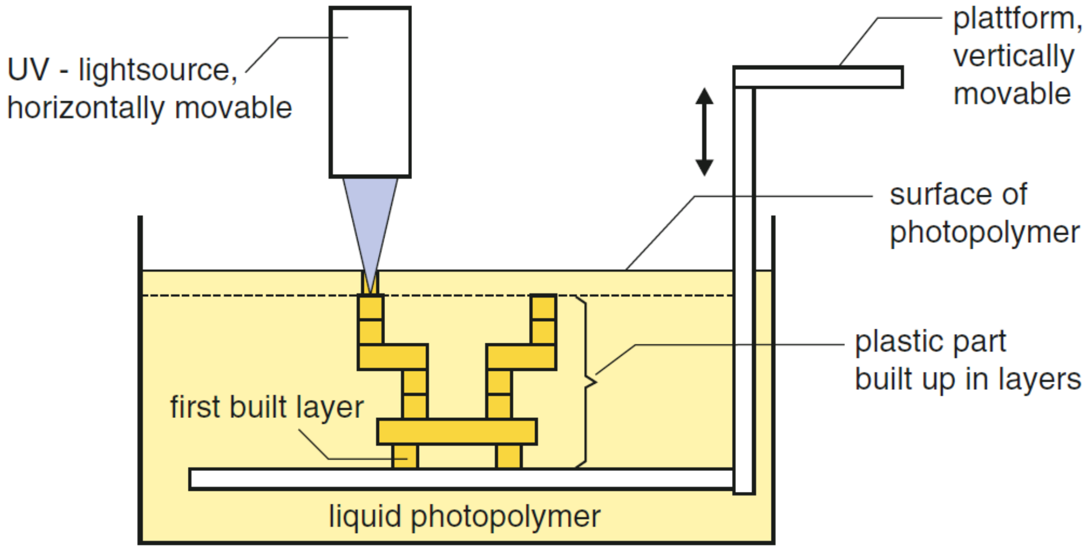


Figure 11. A schematic of the SL method (Poprawe, 2011)

When the last layer of the part has been cured, the platform moves up from the reservoir and the part can be removed from the platform. It is common that support structures have been used during the manufacturing process, especially if the geometry includes overhanging details. The support structures can easily be removed from the finished part and the part is then usually post cured in an UV chamber. The post curing is needed to achieve full polymerization of the produced part, the part is only cured up to 96% during the AM process. (Poprawe, 2011)

SL produces highly accurate parts with good surface quality. Combined with the vast amount of different materials available, SL is a very good method for producing prototypes for functional testing, assemblies and form evaluation as well as for rapid tooling such additively manufactured injection molding tools. Materials for SL developed for rapid tooling include materials such as Somos nanotool and Somos PerFORM which are materials developed to produce strong, stiff and heat resistant parts. (3DSystems, 2017a; DSM, 2017a)

Material jetting is an AM technology that also relies on a liquid polymer, but instead of having the polymer in the same reservoir as the part is being built, as in SL, the layers in material jetting are built by depositing small droplets according to the intended geometry, which are then cured before the next layer is built. Material jetting is however a challenging AM technology, for a number of reasons. As the technology relies on forming very small droplets, commonly around 150µm in diameter going all the way down to 6µm in some applications, the polymer and the hardware needs to be controlled with high precision. The material often needs to be heated to be able to control the viscosity however, the heated polymer is prone to start curing from the elevated temperature which may lead to clogging of the nozzles. The benefits of using material jetting is that the materials can be mixed, the print process is relatively fast and the layers are fully cured during the print process and therefore there is no need for post-curing as with SL technologies. The material jetting process is visualized in figure 12, with the Polyjet build process from the AM machine manufacturer Stratasys. These machines can achieve a layer thickness of down to 16µm and the print head may contain up to 1,536 individual nozzles that can mix different materials.

A commonly used mix for AM IM tools is a material called DigitalABS, which is made by mixing two different polymers inside the machine. (Gibson, 2015; Stratasys, 2017a)

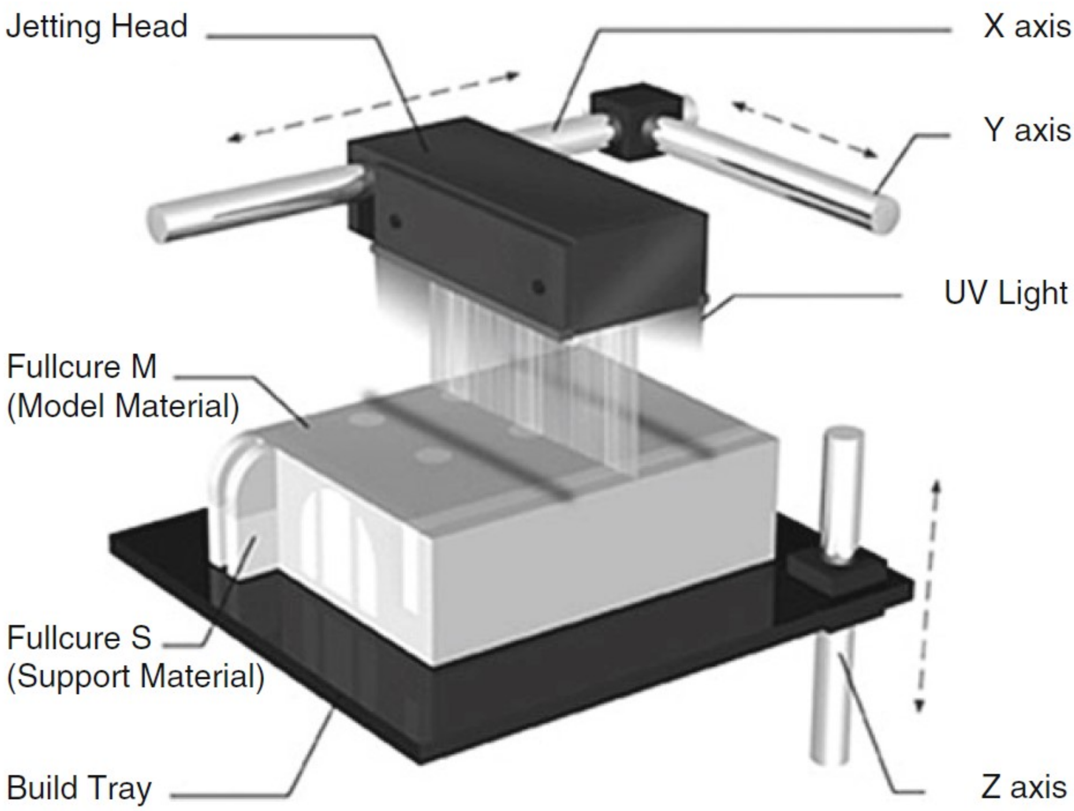


Figure 12. Polyjet AM process by Stratasys. (Gibson, 2015)

Another AM technology is selective laser sintering (SLS). This technology also builds three-dimensional parts layer by layer, but instead of using a photopolymer, as in SL, powder particles are joined together by heat, or sintered. The heat is transferred to the powder by a laser. The SLS technology is a versatile technology as it can be used for polymer parts as well as metal parts. (Poprawe, 2011) A Schematic of a SLS machine can be seen in figure 13. During the build process, the laser scanner projects the laser beam on top of the layer of powder on the build platform. Once the complete projection has been projected on that layer, the build platform inside the build cylinder moves down, by one layer thickness, and the platform in the power feeding cylinder moves up to provide more powder for the recoater. The recoater will then move that next layer of powder over to the build platform. (Gebhardt & Hoetter, 2014)

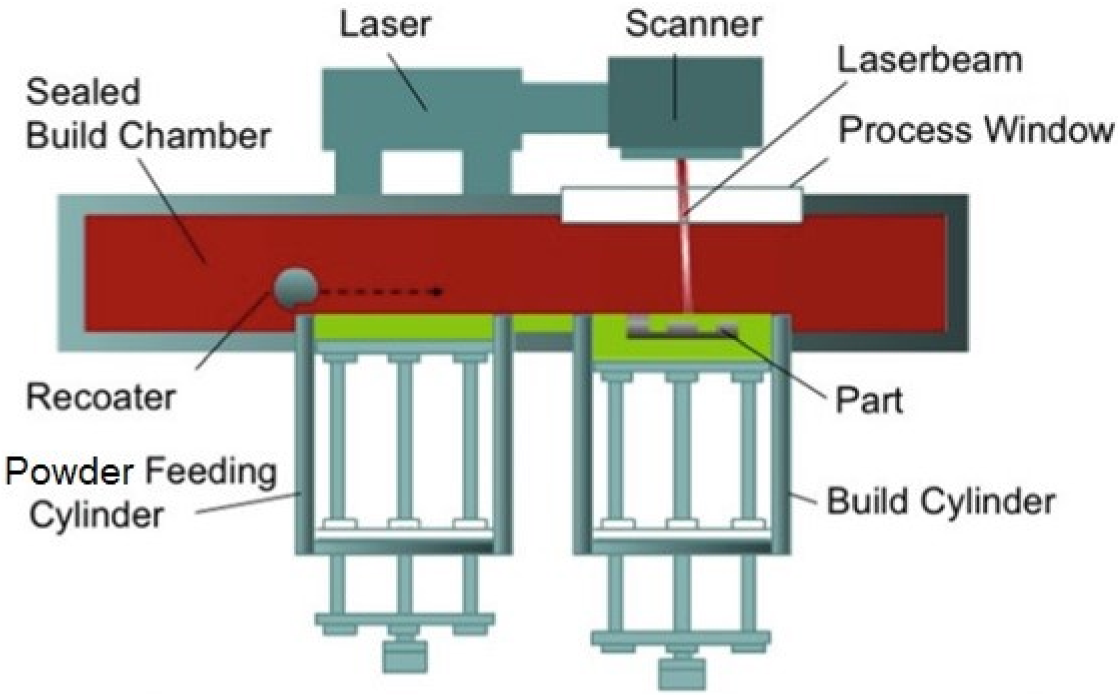


Figure 13. Schematic of a SLS machine (Gebhardt & Hoetter, 2014)

In polymer SLS the build environment is heated close to the melting temperature of the polymer, usually around 200°C, and the laser is used only to add the last energy needed to melt the material. Therefore a 50 W CO_2 laser is usually used for scanning the surface and sintering the layers. Most materials can be used for producing parts with SLS technology, as long as the material is in powder form. However, one of the most common materials used in polymer SLS is polyamide (PA), which produces good functional prototypes due to its good mechanical properties. A downside with sintered polyamide is that the shrinkage of the produced part is quite high, 3-4%, due to the semi-crystalline structure of the material. This makes it difficult to produce highly accurate PA parts. (Kruth, et al., 2003)

The SLS technology can also be used with metal powders mixed with a polymer or a mix of special metal powders to produce metal parts. Indirect metal selective laser sintering (IMSLS) is a process relying on a polymer coat on a metal powder that is melted with a CO_2 laser, with a power output of up to 100W. The melted polymer connects the metal particles together, and this part is known as a green part. However, the part needs to be post-sintered, because the green part has very poor mechanical properties. First the part is inserted in a furnace, which vaporizes the polymer binder and a small amount of sintering of the metal particles can be achieved. This process is known as the debinding stage and the part is called a brown part after the debinding is complete. After the debinding stage, the brown part is entered in a furnace again and a low melting metal, such as copper or bronze, is added to the part. The final part then usually consists of 60% steel and 40% low melting metal. This stage is called infiltration and the part is finished after this stage. (Poprawe, 2011; Gibson, 2015) The different stages of IMSLS are visualized in figure 14.

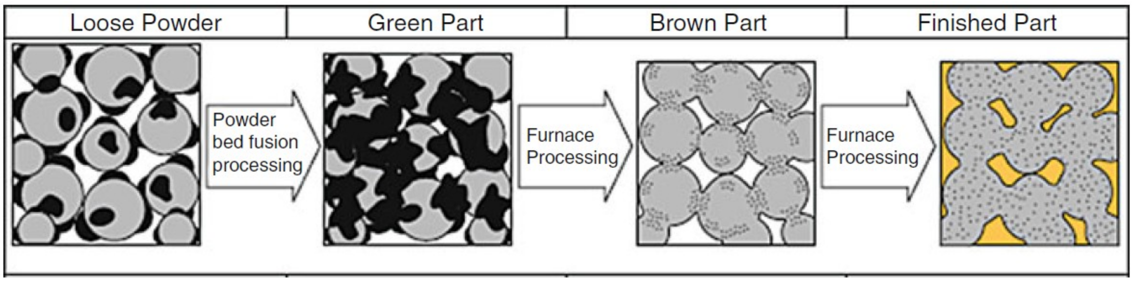


Figure 14. The IMSLS process. (Gibson, 2015)

The brown part can alternatively be further sintered without adding another metal. This method is called consolidation and through consolidation the part is made from only one material, while the infiltrated part is made out of at least two different metals. However, the shrinkage of the part is larger when using the consolidation process than with infiltration. The IMSLS process is widely used for rapid tooling and plastic injection mold tools, and a 316 stainless steel powder, mixed with thermoplastic and thermoset binders, intended for manufacturing of injection mold inserts was introduced already in 1998. (Poprawe, 2011; Gibson, 2015)

Direct selective laser sintering (DSLS) is a process where a mix of high and low-melting metals are mixed, either as separate powders or the high-melting metal coated with the low-melting metal. The process is similar to the indirect selective laser sintering process, but instead of melting a polymer, a laser is used to melt the metal with the lower melting temperature. The benefit of this arrangement is the reduced need for complicated post-sintering processes. (Poprawe, 2011)

While the indirect and direct selective laser sintering processes produce a metal part consisting of a mix of metals, a process known as selective laser melting (SLM) can be used to produce parts made out of only one material. The main difference to selective sintering is that a high powered solid-state laser, with a power output of up to 500W, is used to melt the material. This makes it possible to produce high strength parts out of traditional tooling materials, without any additional binding materials. The mechanical properties can be compared to parts produced with traditional casting processes. The density of the part is however, determined by the relation between the power of the laser and the scanning speed. To achieve a density of 100% density for aluminium, a laser output of 150 W and a scanning velocity of 50 mm/s is needed. A comparison between the densities of parts manufactured with different laser output powers and scanning velocities can be seen in figure 15. The parts are manufactured out of an AlSi10Mg aluminium alloy with a layer thickness of 50µm. (Poprawe, 2011; Buschbinder, et al., 2012)

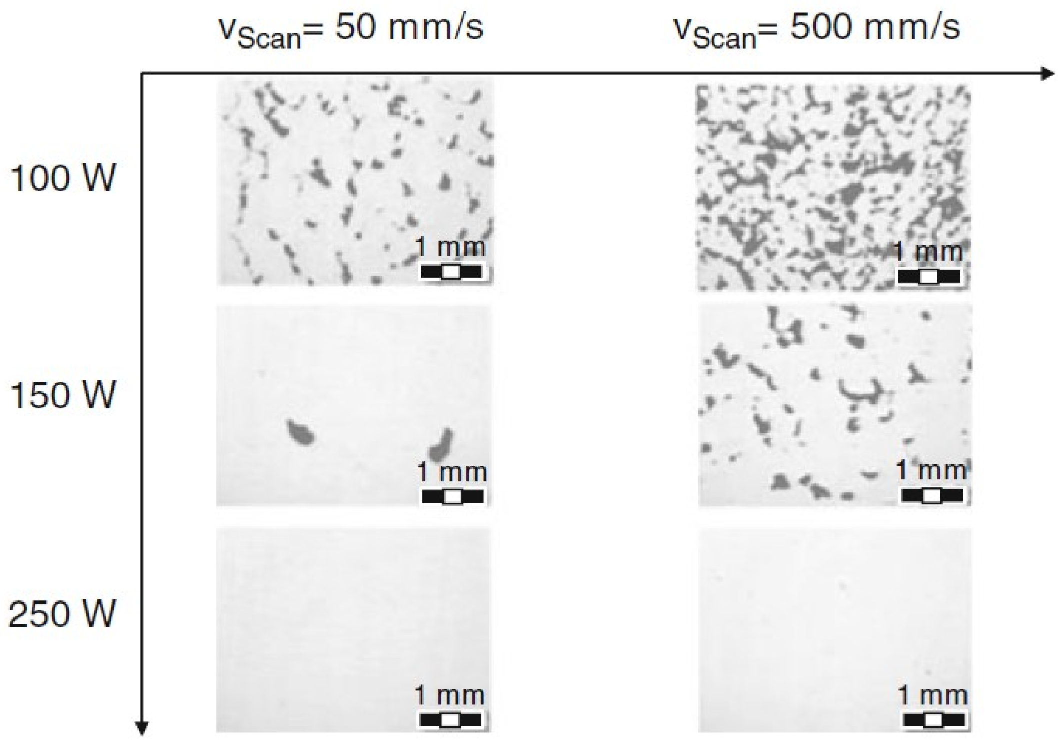


Figure 15. Cross-sections of AlSi10Mg parts manufactured with SLM with different scanning speeds and laser power outputs at a layer thickness of 50µm. (Buschbinder, et al., 2012)

AM IM tools are addressed in the next chapter, based on previous research and case studies from the industry. Included in this chapter is also expectations for the development of the utilization of AM IM tools.

3.5 AM IM tools: previous research & industry examples

The development of the AM technologies and materials has attracted the industries to start experimenting with AM IM tools. The high accuracy and quick build time of the AM machines of today combined with high strength materials that can withstand higher and higher temperatures, drives the utilization of AM IM tools. The most utilized AM technologies for IM tools are the sintering and melting technologies mentioned in chapter 3.4. (Gebhardt & Hoetter, 2014)

Producing prototypes out of the final material and with the intended production method makes it possible to make parts that can be tested in real conditions at an early stage of the PDP. According to a white paper by the AM company Stratasys (2017), benefits of using AM IM tools can improve the time of the PDP by 50%-90% as well as benefits in evaluating the performance of the products in an early stage of the PDP. IM tools have been made by Stratasys using the Polyjet technology, to fill the gap between 3D-printed prototypes and conventional IM molds during the PDP. When manufacturing IM tools with digital ABS, a layer thickness of 30µm can be achieved with details as small as 0.1mm. The Polyjet technology produces a good surface quality on the final parts, so little to no post-processing is needed on the AM IM tools. Stratasys also suggests different methods for producing different amounts of IM parts based on the final material of the parts. This visualization can be seen in figure 16, where material class A contains polyethylene (PE), polypropylene (PP), polystyrene (PS), ABS and elastomers. Class B contains glass-filled PP, polyamide (PA), polyoxymethylene (POM) and polycarbonate-ABS blends (PC+ABS), while class C contains glass-filled PA, PC and glass-filled POM. The last class, class D, contains the most abrasive materials of glass-filled PC, polyphenylene oxide (PPO) and polyphenylene sulfide (PPS). (Stratasys, 2017b)

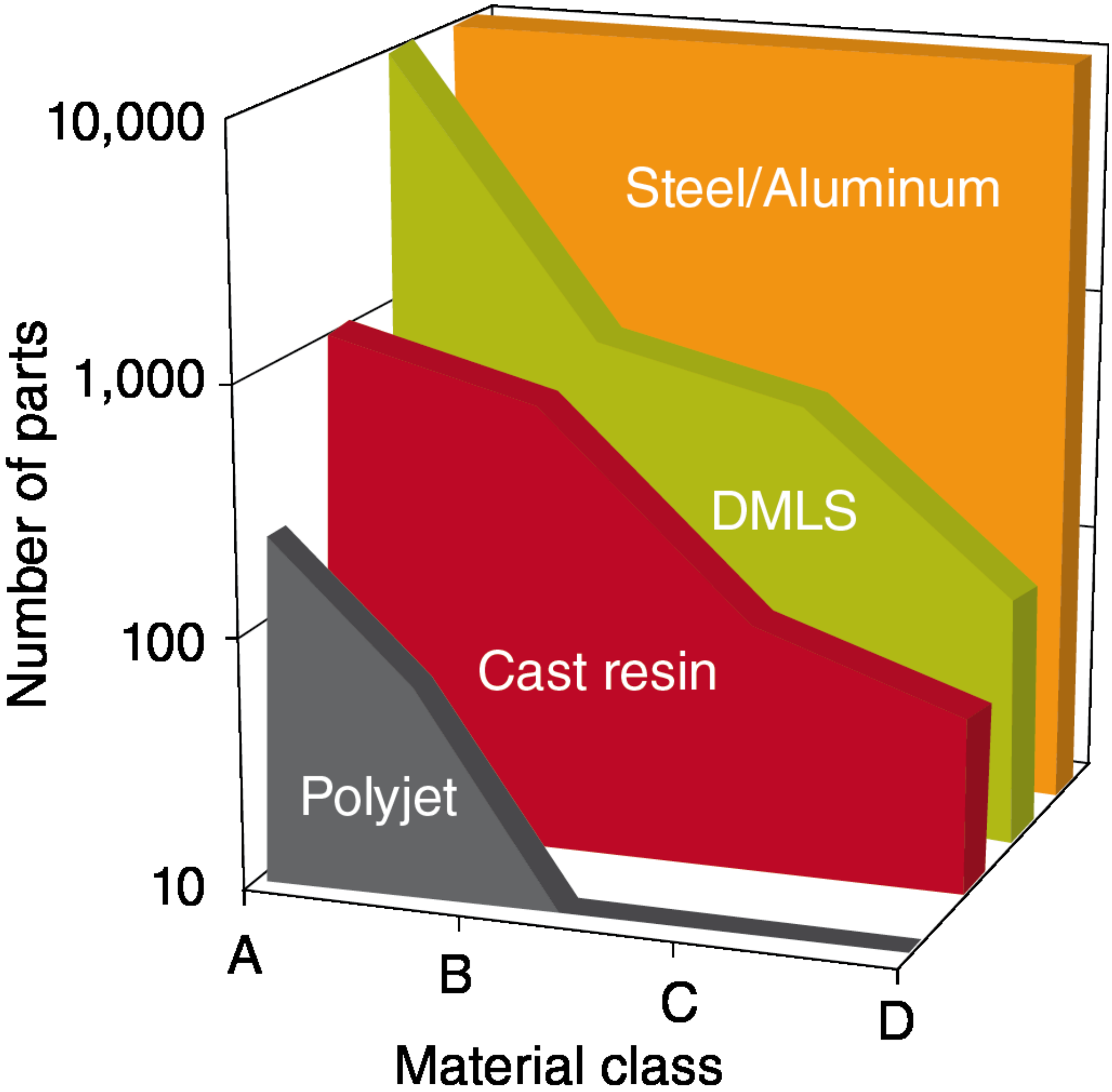


Figure 16. Suggestions on different manufacturing methods based on the intended production amount and part material. (Stratasys, 2017b)

Wehl & Partner is a company that also has tested the use of AM IM tools in their product development. Based on an article published at the web site of material producer DSM, the most successful experiments were made by producing the IM tools with SL technology and using Somos PerFORM material. IM prototypes could be made up to 70% faster with the AM IM tools, compared to producing the IM tools by traditional methods. Parts that were introduced in the article were produced out of 20% glass filled PC, injected at 150°C and in PA 6, injected at 270°C. The tools withstood the production of 40 respectively 47 parts with minimal wear of the AM IM tools. (DSM, 2017b) The final part and AM IM tools can be seen in figure 17.

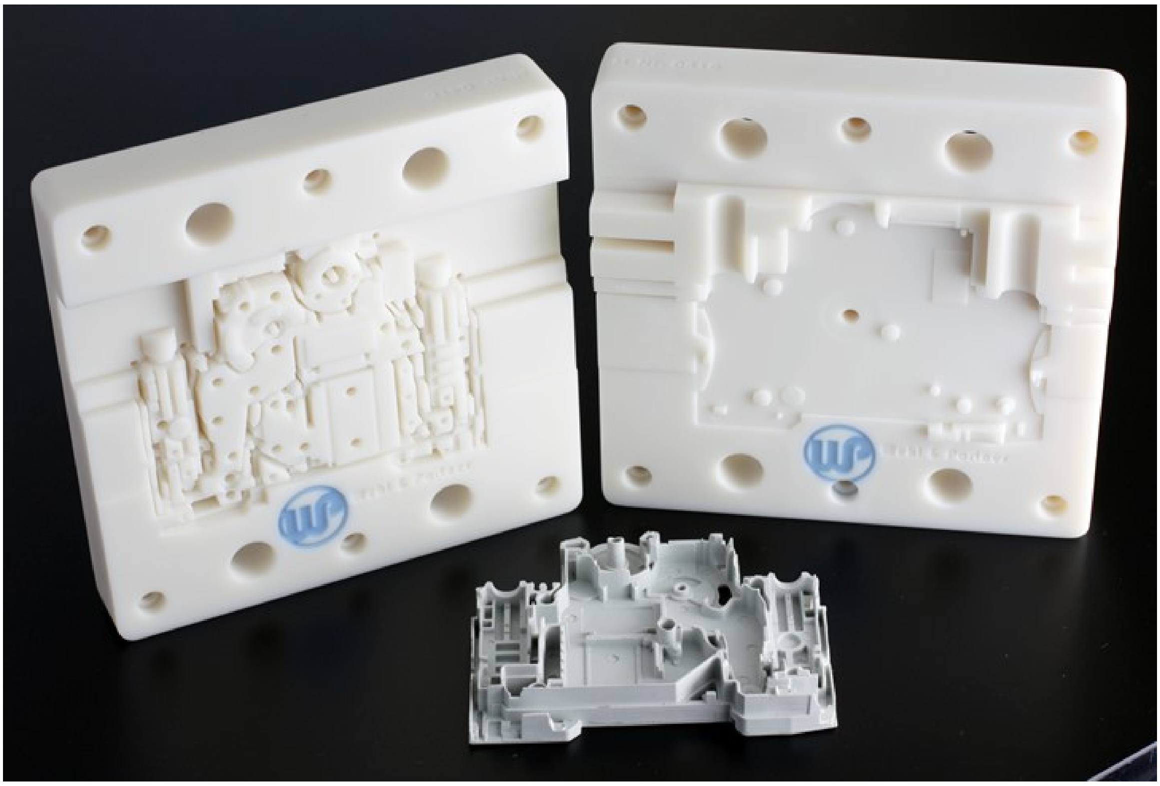


Figure 17. AM IM tools used for producing a part for an electrical switch. (DSM, 2017b)

As AM IM tools show promising results, mold manufacturer Hasco has developed a quick-change mold system to enable a quick switch between AM tools. The Hasco K3500 quick-change mold system was developed to allow for producing small series of products as well as prototypes quickly and cost-effectively. Hasco has tested the approach by manufacturing IM inserts with Stratasys PolyJet AM technology. The inserts were produced to make sealing plugs that could not be manufactured by a conventional IM process. (Stratasys, 2015) The mold inserts and the K3500 mold system can be seen in figure 18.

Figure 18. Hasco K3500 quick-change mold system with AM IM inserts. (Stratasys, 2015)

Buschbinder et.al. (2012) have investigated the skin-core strategy for manufacturing AM IM inserts with conformal cooling with SLM technology. The skin-core strategy means that the outer layers are produced with smaller laser beam and layer thickness than the inner layers of the part. The advantages are a faster build up rate while ensuring a highly detailed part with good surface quality. Based on the experiments done, the density of the inserts was approximately 100% and the overall quality was equal to the results obtained by standard SLM manufacturing strategies. (Buschbinder, et al., 2012) The geometry of the IM insert can be seen in figure 19.

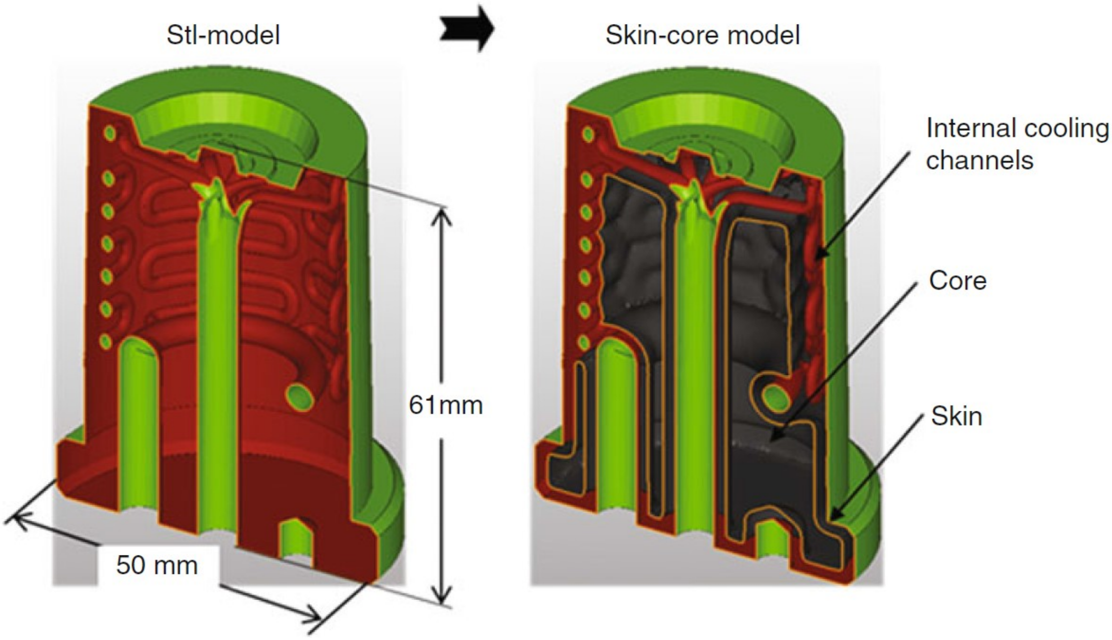


Figure 19. IM insert with conformal cooling, with skin-core manufacturing strategy for SLM manufacturing. (Buschbinder, et al., 2012)

Another tool insert for manufacturing a tooth brush was manufactured using SLM in cooperation between BRAUN GmbH and TRUMPF Werkzeugmaschinen GmbH & Co. KG. The insert was manufactured in six hours and the material used was 1.2343 tool steel. The smallest features on the insert that were directly manufactured with the SLM technology was 0.8 mm and the part only needed minor conventional post-processing through milling and polishing, before it could be used in the production injection mold. The estimated improvement in lead time for producing the insert with SLM technology was 30%. (Buschbinder, et al., 2012) The insert can be seen as printed and after post-processing in figure 20.

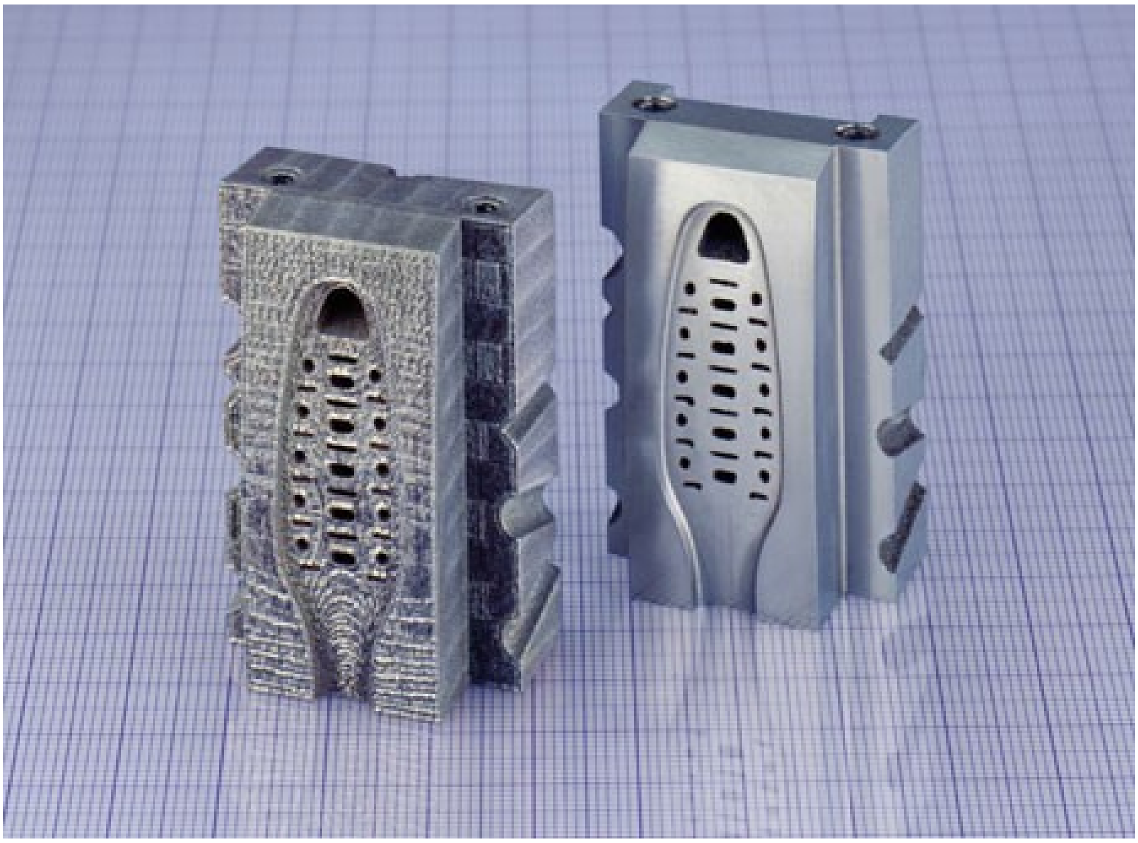


Figure 20. IM insert produced with SLM technology, as manufactured on the left and post-processed on the right. (Buschbinder, et al., 2012)

The use of AM IM tools is however not superior to traditionally manufactured IM tools or directly 3D printing prototypes in all situations. The cycle time for a part using an AM IM tool is usually longer than that of a part made with a traditionally manufactured IM tool, especially when the tool is made from a non-metallic material. The main reason for this is the cooling of the part during the mold process. Also for small quantities of parts that do not require to be produced out of the final material or with the final production method, 3D printing the parts may still be the preferred way to produce prototypes. (Zonder, 2017) Therefore, it is recommended to use AM IM tools only for applications that have complex geometry that is difficult to achieve through conventional tool manufacturing processes or where the lead time to get the parts done are the main factor as well as for small production series. (Gebhardt & Hoetter, 2014)

3.6 Research case: Utilizing additively manufactured injection molding tools during the product development process

After studying the different phases of the PDP, and the vast need of prototypes for different purposes during the process, as well as the complexity of the development and production of injection molded products, the feasibility of using additively manufactured injection molding tools is worth studying in form of case studies. Evaluation of where in the process AM IM tools could be beneficial, is a central part of the study.

3.6.1 Scope and goal of the study

The scope of this study is to evaluate the technical feasibility and process improving advantages of AM IM tools, in the context of product development. The goal is to conduct a practical study, utilizing these tools for products with different complexity, using different AM methods and materials, to provide ABB WA with insight in the benefits and challenges linked to the usage of the AM IM tools and a suggestion of product development segments where this method is inferior to other methods.

From a technology perspective, the study focuses on evaluating different AM methods and materials by designing, manufacturing and using IM tools for prototyping. For the design, traditional IM design rules and practices are followed as far as possible, instead of following the design rules for AM. The reason for this is that the study focuses on the improvement of the product development process of IM products, without compromising the design aspects and final manufacturability of the products. By having the end product in the main focus, this approach means that the tools might not be optimally designed for additive manufacturing or even for additively manufactured tools. The idea is to push the AM IM tools to the limits, to possibly come up with new findings in the utilization of AM IM tools.

The practical part of the study will be carried out by equipping a mold base with AM IM tools and running prototype production runs with the actual material that the final products would be manufactured out of. The purpose of the test runs is to evaluate the strength of the tools as well as evaluating the prototypes in terms of dimensional accuracy, warpage as well as comparing them to parts manufactured directly through additive manufacturing. The practical implementation should also provide information about the needed resources for utilizing AM IM tools, such as post processing and time consumption of the different stages that are involved in the process.

Product development process-wise, the goal of the study is to determine if some of the phases could benefit from the use of injection molded parts early in the process and especially if the benefits could be achieved through the utilization of AM IM tools.

4 Practical implementation: design and evaluation of AM IM tools

The practical implementation of the study is described in this chapter. The setup of the mold used in the study, is presented in section 4.1. This includes the evaluation of the size limitations of products that can be tested in the case studies as well as limitations for the injection molding machine that can be used in the molding process with this mold. Computer Aided Design tools used for the implementation in this study are presented in section 4.2.

The process of choosing the products for the practical implementation is presented in section 4.3. For the selection of the products for the implementations, different attributes are considered for different stages of the testing phase. In sections 4.3.1 – 4.3.3 the design and material evaluation of the injection molding inserts are described as well as the injection molding tests and related parameters. In section 4.4 the feasibility of using AM IM tools for different phases in the product development process for injection molded plastic products is evaluated. The evaluation criteria are described in section 4.5.

The purpose of the practical implementation in this study is to test the technology for using AM IM tools and to evaluate the feasibility of using the method for different phases during the product development process. Most of the tests were done in real development processes to evaluate the impact of the methods in real conditions. By testing a variety of products in different stages of development and using different materials for both the tools and for the injection molded parts, answers to the following questions were pursued:

- AM IM tools in the molding process:
  - Which AM materials are optimal for producing AM IM tools?
  - Can AM IM tools be fitted to the mold and used with minimal post processing?
  - What are the technical limitations and possibilities for using AM IM tools in comparison to using traditionally manufactured tools?
- Injection molding in different product development phases:
  - When are injection molded prototypes inferior to prototypes made with other manufacturing methods?
  - What are the benefits of using AM IM tools versus traditionally manufactured tools or direct 3D printed prototypes?
- Improving the product development process:
  - How should the decisions for different prototyping methods be used?
  - How to ensure that the process evolves over time when using prototypes?

To begin the implementation, the first task was to get a mold frame that could be used for testing purposes. Together with mold experts at ABB WA and CM Tools, two different scenarios were analyzed:

- Using an existing mold frame
- Acquiring a completely new mold frame

The benefits of using an existing mold frame are cost efficiency and reduced time for setting up the test assembly, however some limitations may occur since the specifications of the mold frames were made for a different case.

By acquiring a completely new mold frame, all the specifications for the specific case can be considered, according to the schematics by Lindner & Unger (2002), presented in chapter 3.3.2 of this study. The down side is that acquiring a new mold frame might increase both costs and lead time. However, to make the final decision, the first step in the process of designing a mold needs to be done, that is defining the part design.

The first product examined in this study is a product that is already in production. The purpose of using this product in the first experiments was that the product had a simple geometry and it was easy to design the first mold inserts for this product. Also by using an existing product, the accuracy and stability of the parts made with the AM mold insert could be analyzed and compared to the parts manufactured by the production mold. The first experiments also gave valuable information about machining the AM material and fitting it to the mold plates. The process is described in section 4.3.1. With the knowledge from the first experiment, the process could be evaluated with a product that was being developed.

The second product that was used was in an early stage of development. Additively manufactured prototypes had been made of the part for preliminary testing and geometry evaluation, so it was time for functional testing with prototypes made from the final material for the product and with injection molding as the final production method. The geometry of this product was more complicated than the geometry of the first product, which meant that the mold inserts became more complicated. This lead to some complications regarding the strength of the mold inserts. The process is described in section 4.3.2.

As the first two experiments had been carried out by utilizing plastic AM IM tools, the third and final experiment was to be carried out with metal AM IM inserts. The third product to be tested was a variation of an existing part. The variation of the existing part needed to be tested for functionality but also for testing the automated assembly line. This meant that a larger number of prototypes needed to be made, for which metal AM IM inserts would be a better choice than plastic inserts, due to the higher strength and better possibilities for cooling. The process involving metal AM IM tools is described in section 4.3.3.

The purpose of the practical implementation of the study was to determine both the technical feasibility of using AM IM inserts, in the PDP, and the benefits for the overall product development process for typical plastic parts developed at ABB WA.

The technical feasibility tests were carried out by producing the mold inserts with different additive manufacturing methods and materials and producing injection molded test series of the products. The injection molding processes were monitored and the prototypes were 3D scanned and weighted for quality assurance.

The use of AM IM tools in the PDP was also analyzed by comparing the usage of R&D resources at ABB WA compared to a completely outsourced solution. CM Tools Oy and Proto Labs were used as the outsourcing partners in the practical implementation of the study. The usage of resources is discussed in chapter 4.4.

4.1 Injection mold design process for technical evaluation of AM IM tools

To start the practical testing in this study, a suitable injection mold was needed. Different options were discussed together with representatives from ABB Wiring Accessories and CM Tools of using a Clever Mold System (CMS) mold frame, using an existing mold frame that had been used for producing test parts or ordering a completely new mold. For the first alternative of using the CMS mold frame, the only additional parts needed were the mold plates and an ejector plate setup. By using the existing mold, the mold plates would have needed to be replaced and the size limitations would have been challenging. A new mold was seen as the last alternative if neither of the other alternatives would have worked. Finally, the CMS was chosen as the mold frame for the study. Mold plates and an ejector plate for the mold were chosen together with a representative from Hasco.

Unfortunately, it was later recognized that the CMS mold would not fit in the smaller injection mold machine at CM Tools and that the barrel of the bigger injection mold machine, were the mold would fit, was too big to get stable shots for the small parts produced in the tests. As a solution, a new mold frame was designed around mold plates and an ejector plate, these and all the additional parts were ordered from Hasco.

The mold was designed as a cold runner, two-plate mold, with one cavity and a sprue running in the middle of the cavity mold plate. The mold cavity was located on the side of the sprue, leaving the possibility to add another cavity symmetrically on the other side of the sprue. A conventional gate was designed between the runner and the part and ejector pins were designed for ejecting the part. There were no cooling or tempering designed into the mold at this point, so the additively manufactured mold inserts were to be cooled between shots using pressurized air.

A 3D model of the entire mold was designed at CM Tools using PTC Pro/E software. This 3D model can be seen in figure 21. Later, the core and cavity inserts were also modeled at ABB Wiring Accessories in PTC Creo Parametric 2.0, so that they could be used as a base for customized mold insert design using the PTC Creo Mold Extension tool.

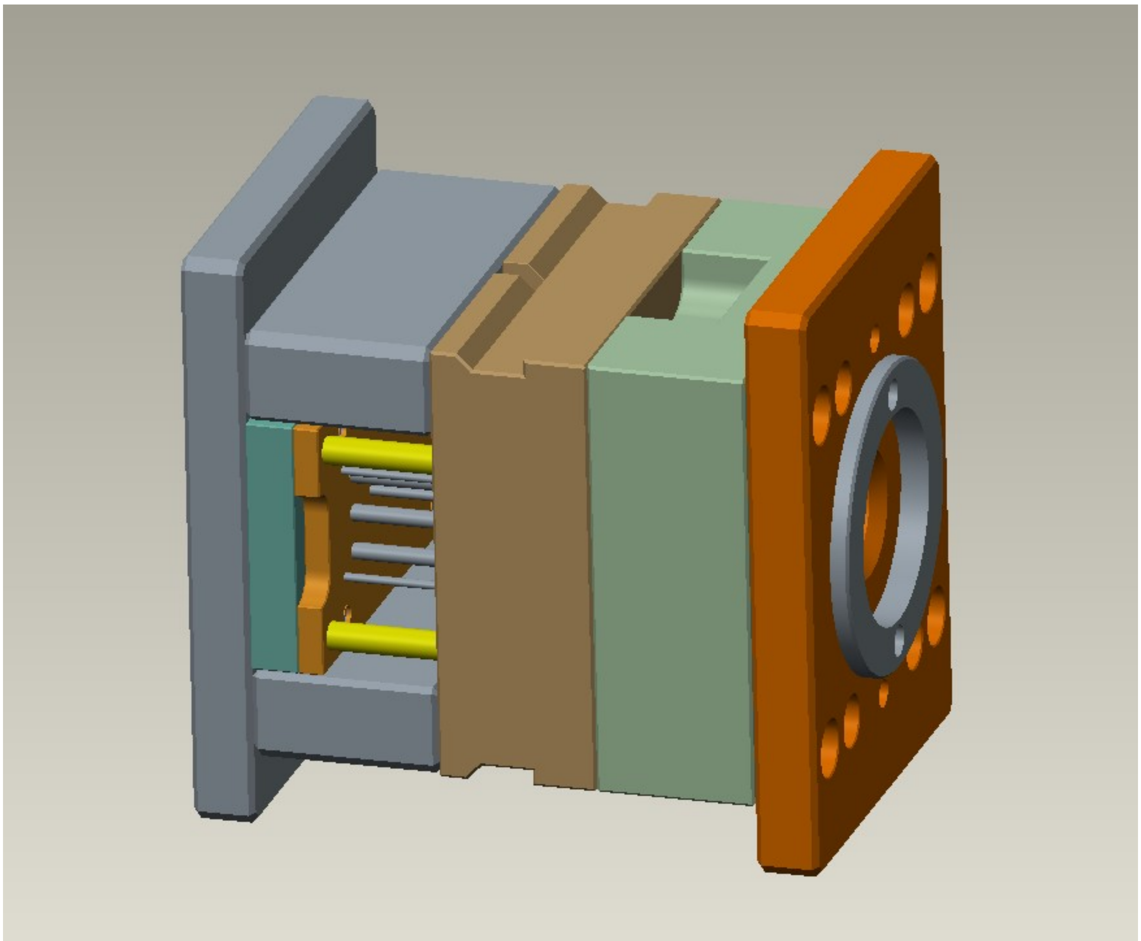


Figure 21. A 3D model of the mold used for testing the AM IM tools

As the mold was designed specifically for prototype production and testing, some of the stages of mold design presented in chapter 3.3.1 were neglected or chosen in a different priority than suggested in the mold design model by Lindner & Unger (2002). The deviation from the model was the neglecting of a tempering system and choosing the mold before choosing the injection molding machine. Later, a tempering system was however designed, for the test with DMLS manufactured aluminium inserts.

4.2 Computer Aided Design tools for effective use of AM IM tools in the PDP

Computer Aided Design (CAD) tools can be used to make the utilization of AM IM tools more effective. As the CAD tools are already used in other tasks during the product development process, the usage of the same tools for streamlining stages of producing AM IM tools was analyzed.

The CAD tools that were chosen for this study was PTC Creo Parametric 2.0 and Simcon Cadmould, as these are tools that are in use at ABB WA. The goal was to investigate how these tools can be used to make the use of AM IM tools faster by standardizing the modeling process and introducing effective geometry analysis to ensure the feasibility of the design before manufacturing the inserts. The scope of the usage of these CAD tools were determined by the findings in the case studies presented in the next chapter and learnings from the literature study.

4.2.1 Computer Aided Design process of IM inserts

The CAD mold frame and inserts were designed by CM Tools, as the mold frame was assembled there. The model was designed using PTC Pro/E CAD software. Once the mold, including the mold inserts, was modeled it could be reused for the rest of the test runs. The first 3D model of the mold that was designed can be seen in figure 22.

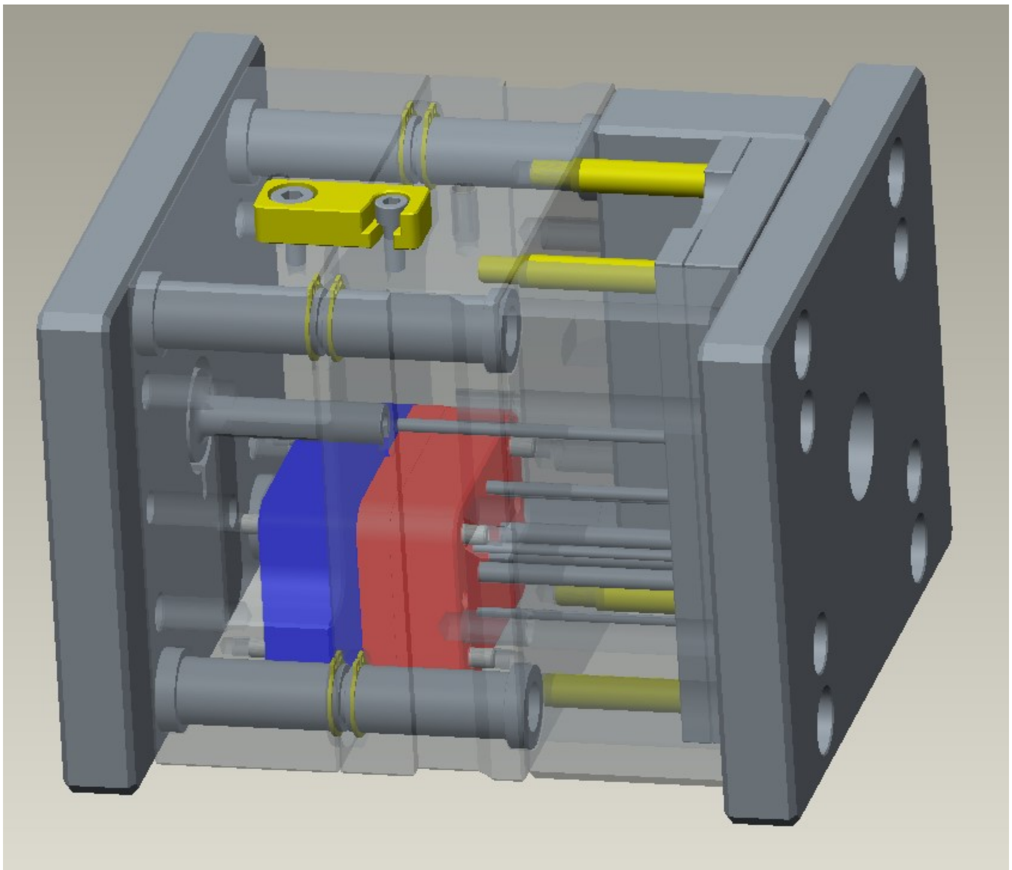


Figure 22. The first 3D model of the mold. The red and blue parts represent the inserts.

The CAD model of the mold could be imported as a STEP file into PTC Creo Parametric 2.0 which is used at ABB WA, and in this way, it could be incorporated into the workflow at ABB WA. Having a CAD model of the entire mold gives the possibility for the design engineer to keep track of the ejector plate and the core mold plate, for reuse of ejector locations for different inserts when possible and detection of problems due to intersecting ejector pin holes. The addition of ejector holes is demonstrated in figure 23.

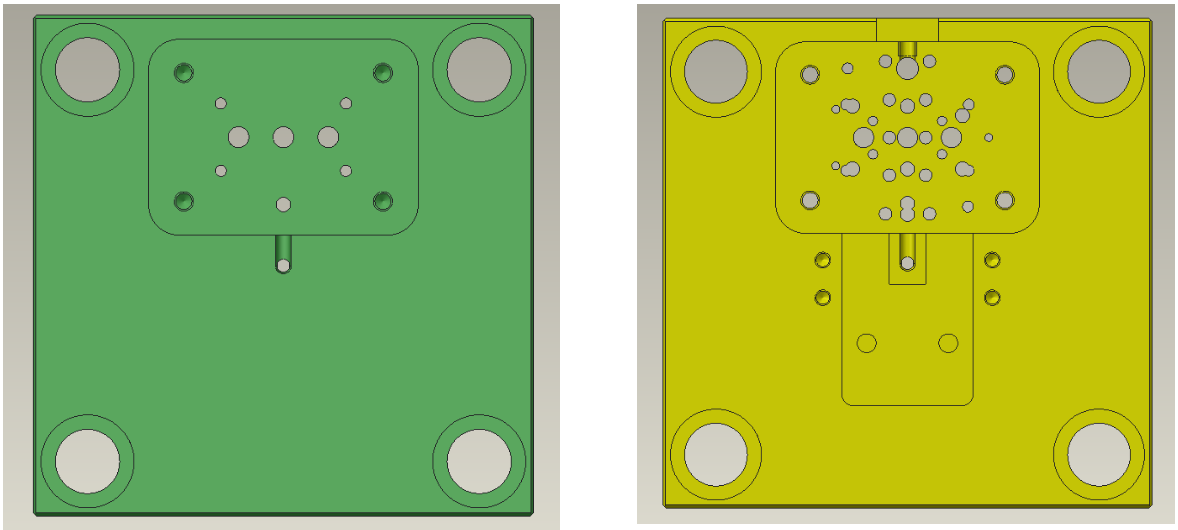


Figure 23. A visualization of the core mold platen prepared for the first test part (green) with ejector pin holes and insert pocket. The same plate (yellow) after added holes and pockets for the second and third parts.

The core and cavity inserts, the ejector side mold platen and the ejector retainer plate are the parts that are changed for different geometries, while the rest of the mold frame mainly stays the same. When the inserts have been modeled and the locations for the ejector pins have been inserted to the core insert, the ejector pin locations can be replicated to the mold plate and ejector plate for machining. Therefore, the process of modeling different inserts for different parts was studied, to examine ways of streamlining the process and reduce the overall time of the PDP. Although, for most cases only the inserts, ejector side mold platen and ejector plate needs to be modified, the some additional modifications needed to be made to the mold frame during the implementation of the aluminium inserts. Pockets for sliders were modeled into the mold platens as well as cooling channels for running tempering water through the inserts. These modifications are visualized in figure 24 and figure 25.

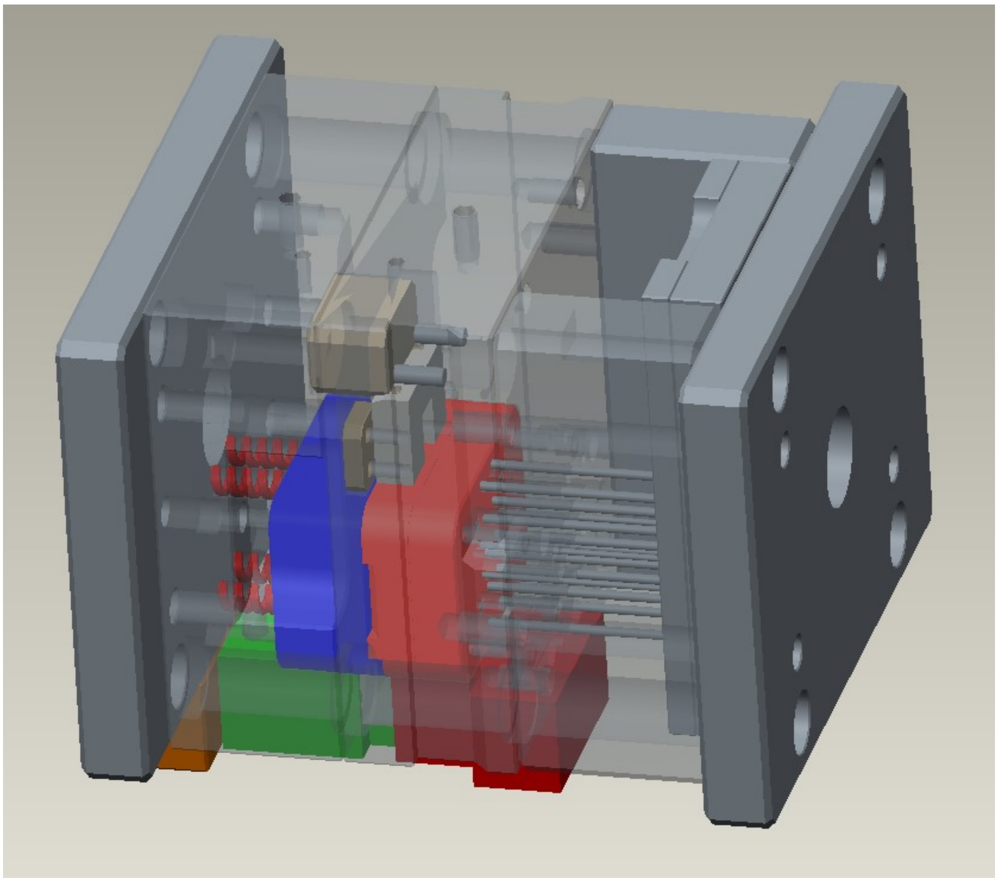


Figure 24. The modified mold for aluminium inserts.

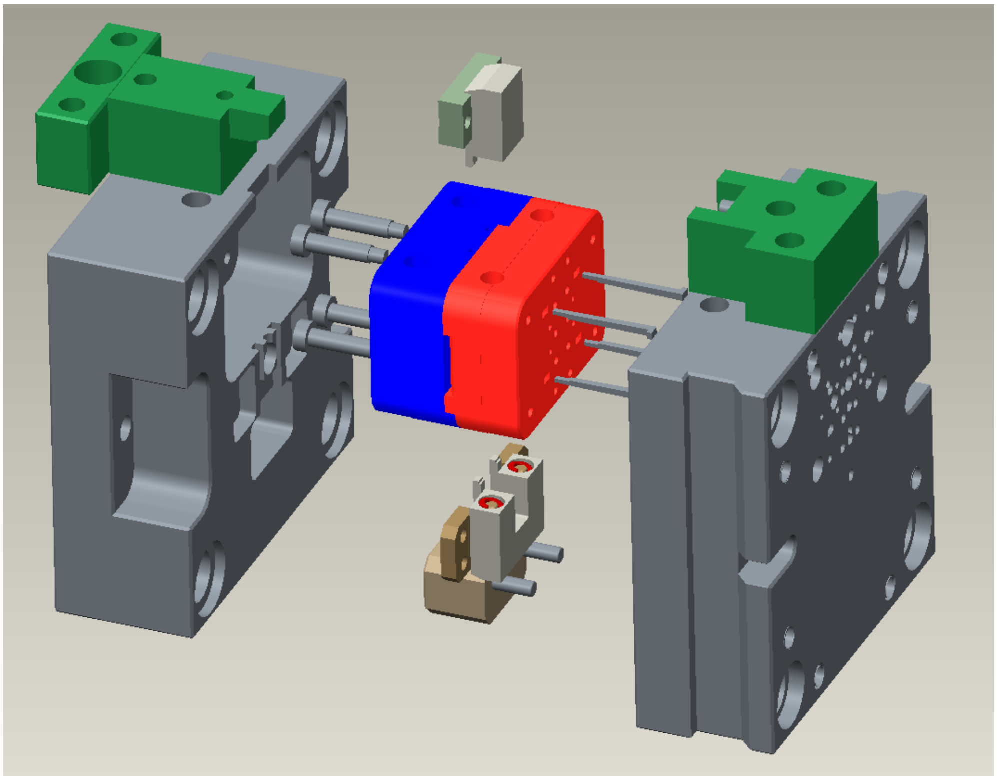


Figure 25. Exploded view of the inserts, sliders and mold platens that were modified for the aluminium inserts.

4.2.2 Injection molding process analysis and simulation

As described in chapter 3, a common practice for minimizing the risks for failure during the molding process, is to analyze the process by using simulation software. The simulation software Cadmould was used in this study for analyzing the injection molding processes, as it is the software used at ABB WA.

Before manufacturing new molding tools, a simulation of the mold process can reduce the time of the product development process both by ensuring that the additively manufactured inserts will not break but also by providing valuable information about the part itself. Simulations can provide information such as warpage, shrinkage and sink marks. By recognizing these problems in an early stage, the product development lead time can be reduced. (Kazmer, 2007)

There is however a risk of not being able to replicate all of the conditions accurately in the simulation, which leads to the need of physical prototype testing. One way of doing this physical testing is using AM IM tools. To study the comparability of simulation results and physical prototypes, simulations were made using the Cadmould software and the results were then compared to the result from the prototyping tests with AM IM inserts.

The purpose of the simulations done in this study was not to optimize the IM process, but rather to study how the output of the simulation corresponds to the results from the tests done with the additively manufactured injection molding tools. The results could then be used to improve the product development process by defining which benefits both methods bring to the process.

First the production part was simulated in Cadmould using the same parameters used in the test runs. For the simulation of the part, the parameters used in the simulation and the corresponding values from the actual test run can be seen in table 3.

Parameter	Value in simulation	Value in test run
Filling time ($t_{filling}$):	1.2 s	1.22 s
Melt temperature (T_{melt}):	220°C	220°C
Wall temperature (T_{wall}):	40°C	-
Ejection temperature (T_{eject}):	95°	-
Filling flow rate:	6.107 cm^3/s	9.508 cm^3/s
Packing pressure profile:	150 bar 0-1.5 s, 50 bar 1.5-3 s	150 bar 0-1.5 s, 50 bar 1.5-3 s
Cooling time inside mold after filling ($t_{cooling}$):	60 s	60 s + 10 s with mold open

Table 3. Simulation and test run parameters.

The values used in the simulation corresponded to the parameters of the test run done with the highest packing pressure profile. The wall temperature, T_{wall}, of the AM IM mold inserts could not be controlled during the practical implementation as there were no tempering system available in the mold at the moment. Also, the ejection temperature, T_{eject}, could not be measured during the tests, which lead to the cooling time, $t_{cooling}$, of 60 seconds to ensure that the part had cooled down enough before ejection from the mold. For the simulation, T_{wall} and T_{eject} were set according to the recommendations for the material. The material set in Cadmould was a glass-filled PP similar to the glass-filled PP used in the practical implementation, as the exact equivalent material was not found in the Cadmould material library.

The results from the simulation were used to ensure that the part would be possible injection mold, with a reasonable filling pressure. The results were also used to predict and compare the warpage of the part with the parts produced in the practical implementation. In figure 26, the filling pressure in the part is visible. As can be seen from the picture, the maximum filling pressure is 93.2 bar, which is significantly less than the recommended maximum filling pressure of 100 MPa. The blue areas in the pictures are areas where the pressure has dropped to zero, which indicates that these areas have already cooled down so much that the material has solidified.

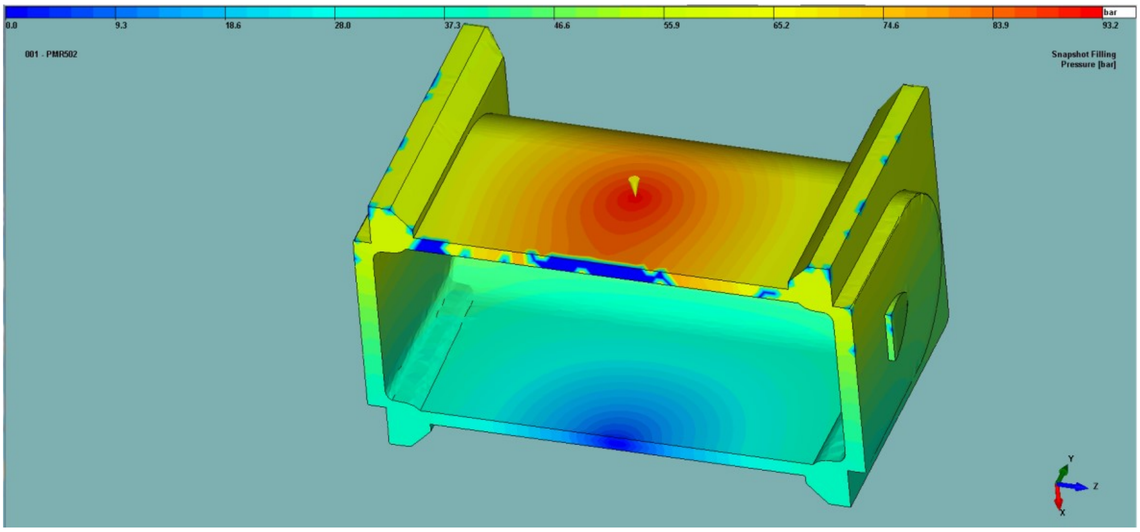


Figure 26. Simulated filling pressure in the part at the end of the filling phase.

Based on the indications from the pressure distribution in the part, the actual solidification of the plastic in the part can be simulated by analyzing frozen layer thickness in Cadmould. Results show that the lower edge close to the injection point is starting to solidify already when only around 60% of the entire part has been filled. The areas displayed in red in figure 27 have completely solidified.

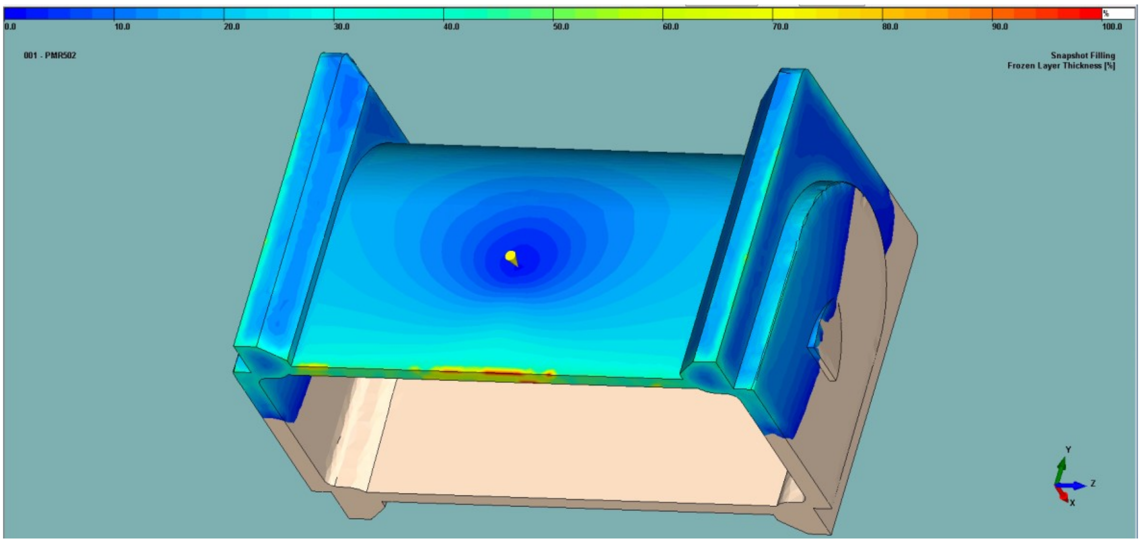


Figure 27. The areas in red have completely solidified, although only 60% of the part is filled.

This means that these areas will not be affected by the packing pressure and due to uneven shrinkage, the edges will most likely suffer from warpage. The final warpage of the part can be seen in figure 28. As predicted by the simulation results presented earlier, the edge closest to the injection point will suffer from significant warpage. However, according to the simulation the corresponding edge on the other side of the part will warp even more. In figure 28, the visual deformation has been amplified by a factor of two, to better visualize the impact of the warpage on the final part. The maximum warpage of the part, according to the simulation, is 0.625mm. The average shrinkage of the simulated part is 0.8%.

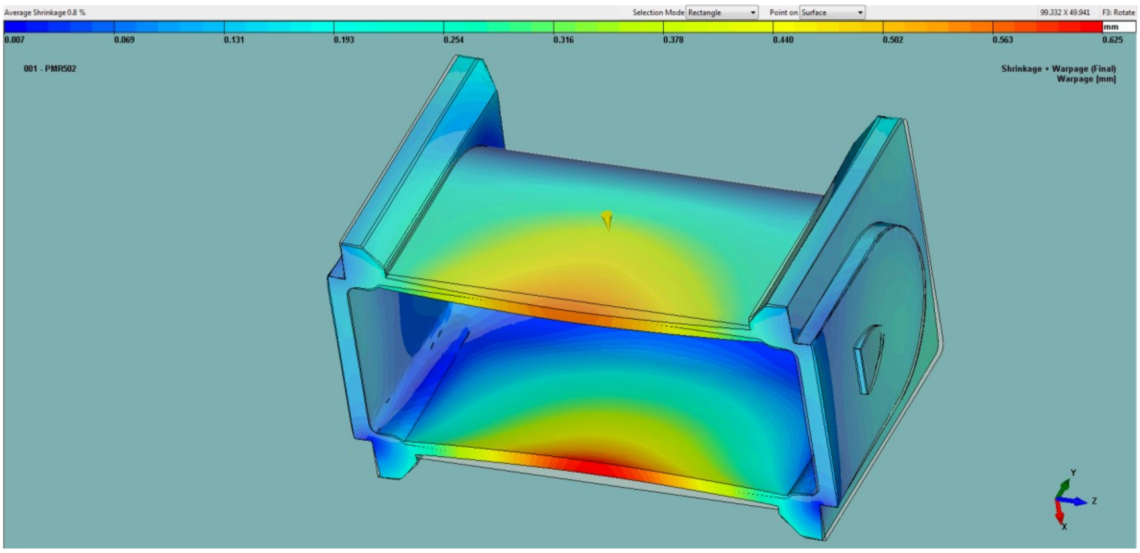


Figure 28. Final warpage simulation, affected by shrinkage and warpage of the part

4.3 Practical implementation of AM IM tools

For gathering information about the technical side of using AM IM tools and analyzing the benefits of introducing the methods into the PDP process of injection molded plastic parts, different parts were used in the case studies. These parts were:

- A product that is already in production; used for benchmarking the additive manufacturing technology
- A new product in early design stage; used for functional testing of assembly features
- A new variation of an existing product; used for compatibility testing in existing assembly and for automation line testing

For all three case studies, the same mold frame was used and all the test runs were done with the same molding machine. The molding machine used to test the AM IM tools was an Engel 80/40 Duo. The machine can be seen in figure 29. The different case studies will be presented in detail in the following sections.

Figure 29. Engel 80/40 Duo injection molding machine used in the case studies.

4.3.1 Case study 1: Production part used for benchmarking

The first product to be used for testing was an interconnector that is used for connecting mounting boxes to each other. This part has been in production for a long time and was therefore a good choice for benchmarking. The reasons for choosing this part was that it was the right size, it had a fairly simple geometry and as it was in production it would be easy to compare the results of the prototypes to the actual production part. Although the parts' geometry was simple, a few features were left out to simplify it further. Small features near the parting line were left out to minimize the risk of the additively manufactured mold inserts to break during the injection molding process. The original part geometry can be seen in figure 30 and the simplified version can be seen in figure 31.

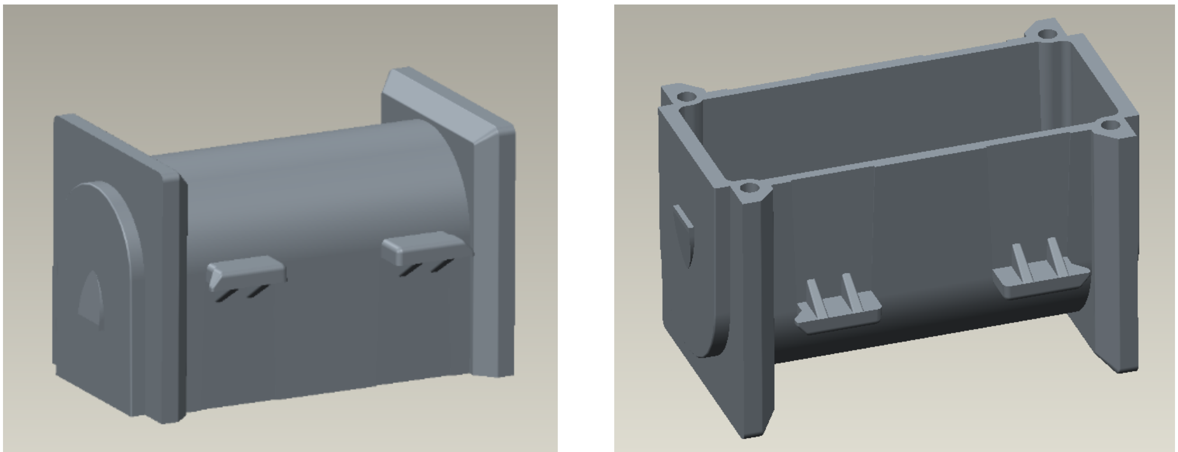


Figure 30. The original production part used as a base for the first test runs

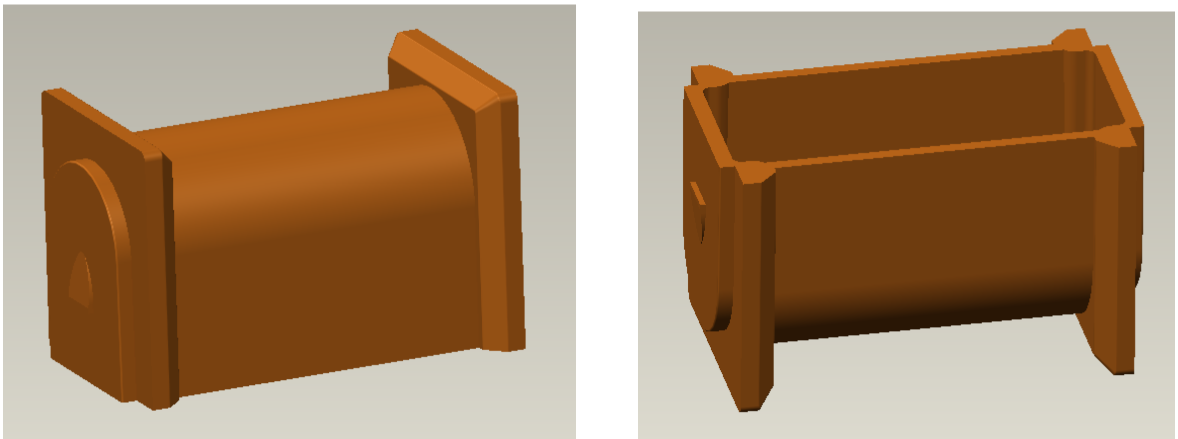


Figure 31. The simplified version of the production part that was used for testing

When the part had been simplified it was prepared to be used as a reference part for the mold insert design. The CAD model of the part needed to be scaled up to compensate for the shrinkage of the part due to the nature of the injection molding process as described in section 3.3.2. The shrinkage for the material used for the product was 0.5% according to the material data sheet, so the CAD model was scaled up with a factor of 1.005. This model was then inserted as a reference model to design the mold inserts. The locations and sizes of the ejector pins were then added to the mold inserts. The specifications and locations of the ejector pins were copied from the production mold, with a few exceptions. The 3D model of the IM inserts can be seen in figure 32.

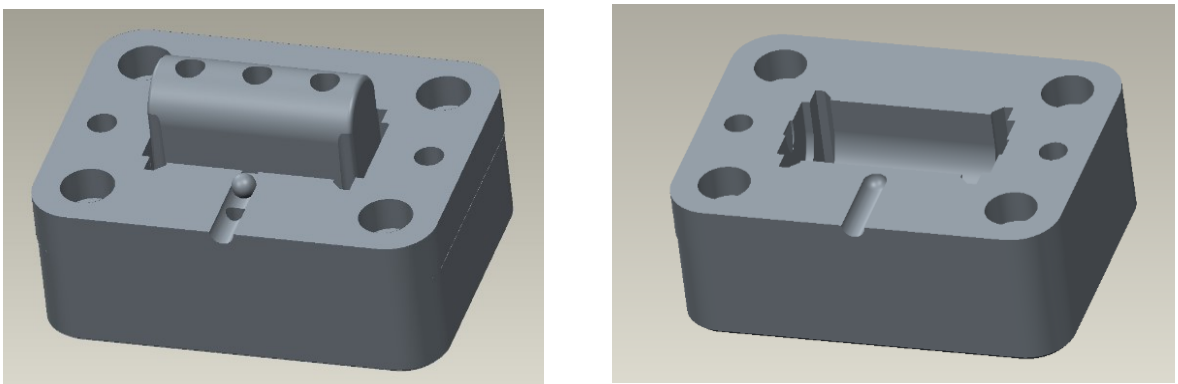


Figure 32. 3D-model of the IM inserts for the production part prototype

When the design of the mold inserts was ready, the CAD files were converted to STEP format, and sent by CM Tools to Maker3D for printing. The material used for the first AM IM inserts was Accura Bluestone. CM Tools had been using this material in earlier experiments with AM mold inserts, and suggested the use of this material for the first experiment. Accura Bluestone is a heat and abrasion resistant material with a tensile strength of 66-68 MPa, which makes it suitable for using in prototyping mold inserts. (3DSystems, 2017c)

The inserts were manufactured with a ProX 800 printer by 3D Systems, which uses SL as the printing technology. In addition to the Accura Bluestone material that was used in this study, a wide variety of other materials can be used with this printer, such as PP-, PC- and ABS-like materials as well as ceramic reinforced composites and temperature and moisture resistant materials. (3DSystems, 2017b)

The build envelope for this printer is 650x750x550 mm and the accuracy of the parts produced is ± 45 µm. Features as small as 0.1 mm can be printed, which is enough for the insert manufactured for this study. (3DSystems, 2017b) The ProX 800 printer can be seen in figure 33.

Figure 33. The printer used to print the AM inserts with Accura Bluestone material (3DSystems, 2017b)

The design process for the first AM IM inserts took three weeks. The lead time for manufacturing the first inserts was two weeks. With an additional week of machining the inserts and fitting them to the mold platens, the total time of receiving the first test parts, was five weeks.

When the inserts had been fitted to the mold platens, a test run was made to test the functionality of the mold. PP was used for the first few shots, instead of the final material which was PP with 20% glass fiber. PP was chosen for the first shots, because of the better flow characteristics and lower abrasive qualities than the PP with glass fiber. This way the right shot size could be found quickly without a risk of damaging the mold inserts. The cavity insert fitted to the mold platen can be seen in figure 34.

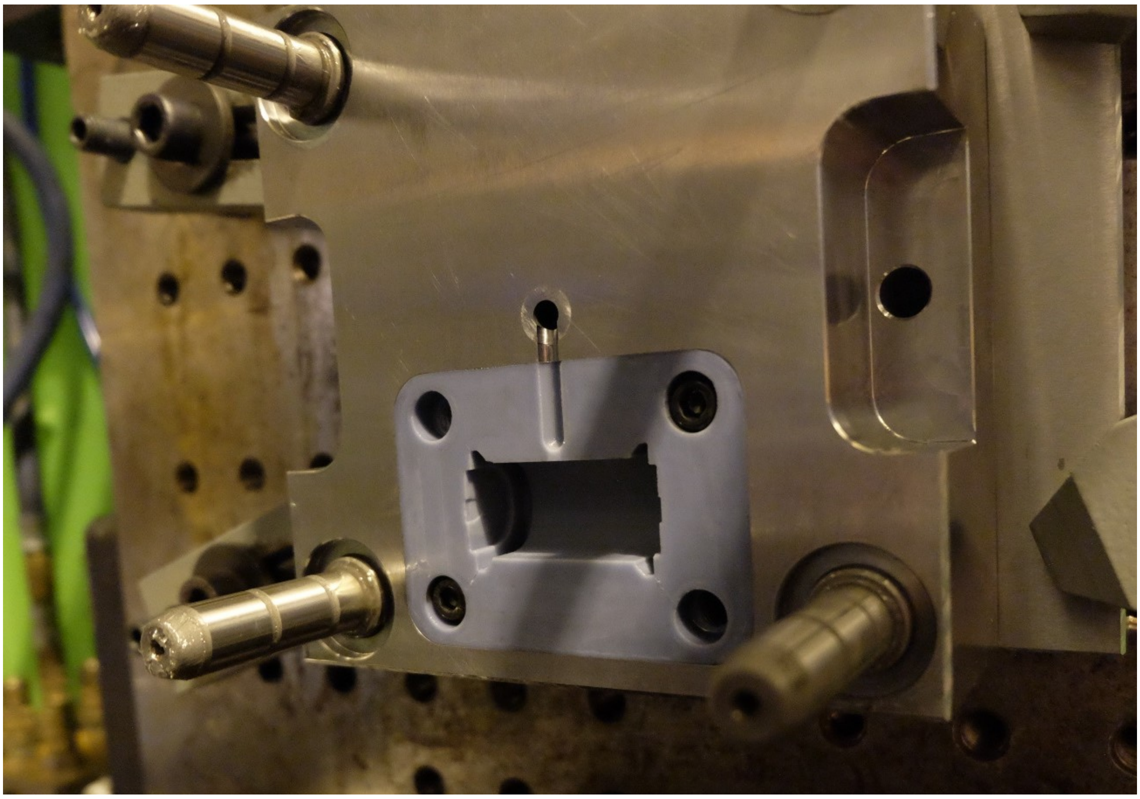
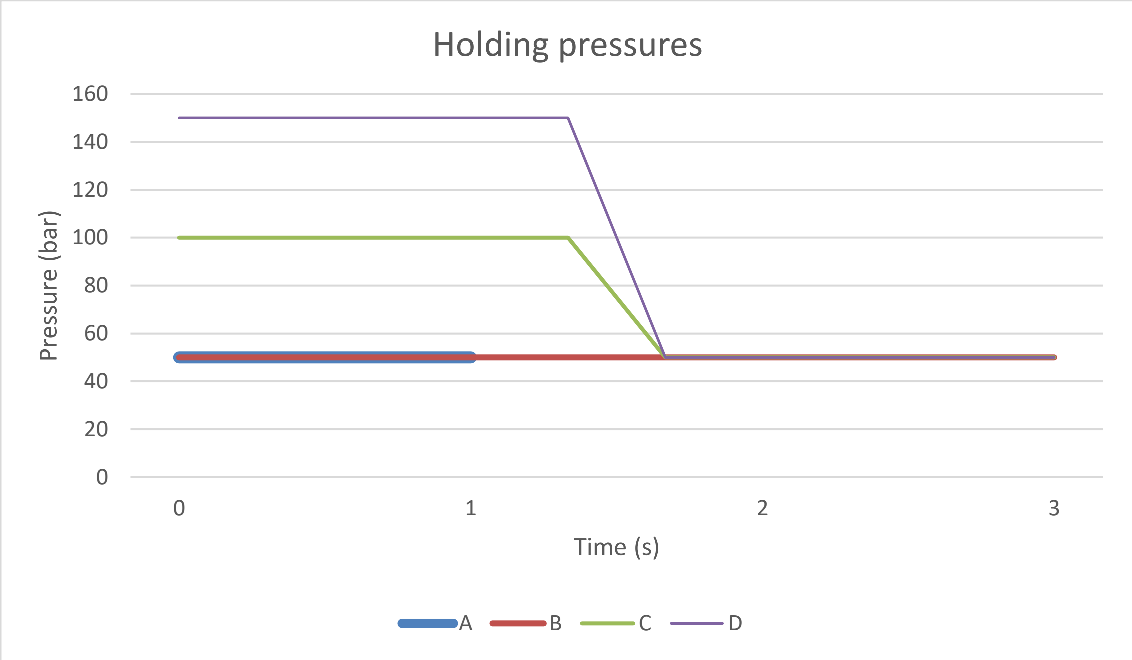


Figure 34. Cavity insert, manufactured out of Accura Bluestone material, fitted to the mold platen.

It took three shots to get the right shot size for the part and after that, two complete parts were made with polypropylene. The rest of the parts were made from PP with 20% glass fiber. Four different holding pressure profiles were used during the different test runs to see if the warping could be reduced. The eight first parts were made with profile A, the next three parts with profile B, next three with profile C and the next three with profile D. The different holding pressure profiles can be seen in graph 1.



Graph 1. Holding pressures during test runs of the production part prototype.

The first parts were manufactured with a holding pressure of 50 bar, for one second. The conservative usage of holding pressure in the beginning was due to evaluating whether a lower holding pressure would result in less flashing on the parts. The holding pressure was then gradually increased, to be able to control the shrinkage and in turn the warpage of the part. First only the holding pressure time was increased from one second to three seconds and three parts were molded with this holding pressure profile. The next three parts were molded with a profile of 100 bar for 1.5 seconds and then 50 bars for 1.5 seconds. The rest of the tests were done with a holding pressure of 150 bar for 1.5 seconds and 50 bar for 1.5 seconds. To evaluate how the different holding pressure profiles impacted the final parts, three parts of each set was measured using video measurement equipment. The measurement process and results are described in chapter 5.1.1.

The testing was continued with the holding pressure profile D until a total of 50 parts had been made. This was done to evaluate the degradation of the mold inserts. The conclusion was that there was significant wear to the mold inserts after 50 shots, but the mold inserts were still intact and could be used for producing parts. After a total of about 30 shots, the flashes became gradually worse, because the core insert had cracked, and the plastic was pushing into the cracks during the injection molding process. The cracks are clearly visible in figures 35 and 36.

Figure 35. The cavity insert cracked along the edges, which lead to increased flashing in the prototypes.

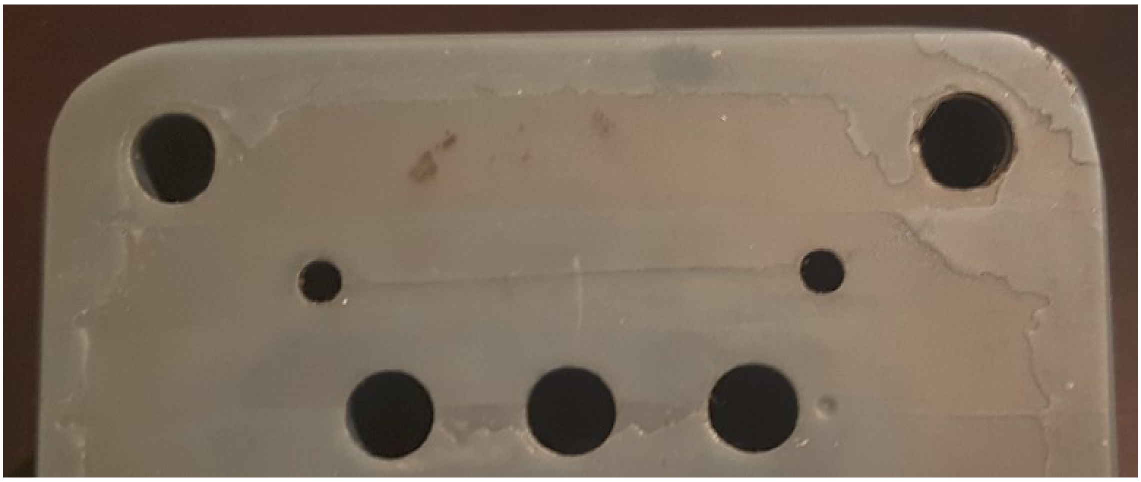


Figure 36. The core cracked all the way through, between two ejector pin holes.

From the first test run, it could be concluded that the use of Accura Bluestone, as material for the IM inserts, is feasible. However, there was some issues with the material when preparing it for the mold process. These problems had to do with the layering effects that comes with additive manufacturing and some brittleness of the material. As the parts were machined to fit the mold platens, some of the layers stripped of unevenly, as can be seen in figure 37, as well as the cracking of the inserts during the IM process. There was also an issue with drilling the holes for the ejector pins, as parts from the insert was cracked off and had to be fixed with some metallic paste, as can be seen in figure 38. The metallic paste started to fall off during the test runs. However, the impact on the prototypes was minimal.

Figure 37. The layers were unevenly machined off during fitting of the inserts to the mold platens.

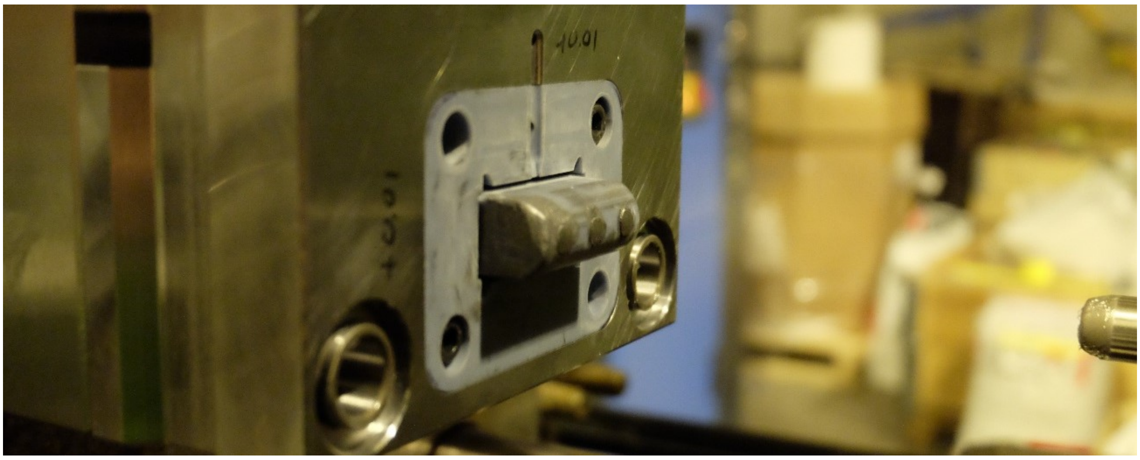


Figure 38. AM IM insert fitted to the mold platen. The edges of the insert needed to be fixed with some metallic paste because they were cracked during the drilling of the ejector pin holes.

The use of PP with 20% of glass fiber, for the material of the test part, was equally feasible. The mold did not get significantly damaged by the material and the parts were completely filled. Due to the lack of cooling in the mold and the conservative use of holding pressure during the mold process, some warpage was noticed along the long, flat sides of the parts.

The ejection of the parts from the mold core worked well. There were some issues however with the ventilation of the mold, as some signs of gas pockets could be seen on the deep core side of the part. The ventilation problem has mainly to do with the geometry of the part, as there is a complete lack of drafts on the inner sides of the part.

The functionality of the prototypes was assessed by assembling the prototypes with the corresponding products that the part is intended for. The part worked as intended although the fitting was not as tight as for the production part, due to the simplification of the part. The assembly for evaluating the functionality of the prototypes can be seen in figure 39.

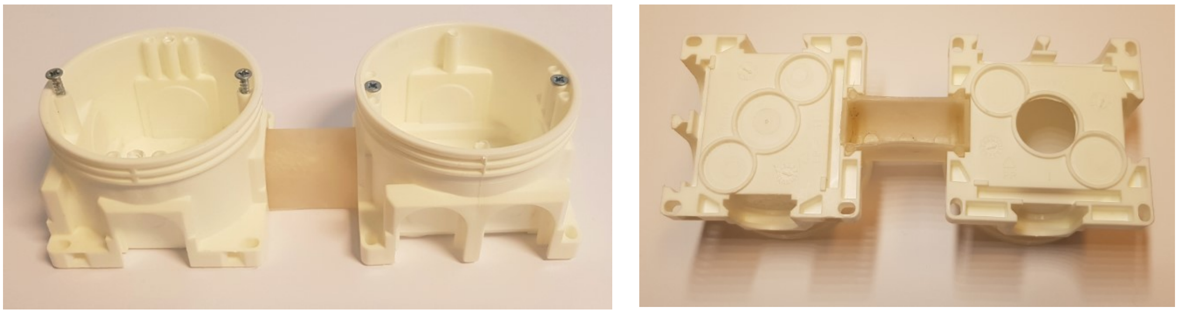


Figure 39. Interconnector prototype assembled with actual mounting boxes

The process of designing and acquiring the AM IM inserts was slower than anticipated. By analyzing the process, the bottlenecks were recognized to be the following:

- The design lead time could be decreased by having a standard process for modeling the inserts
- The lead time of acquiring the AM IM inserts could be improved by using a subcontractor with better delivery times
- The time for fitting the inserts to the mold plates could be improved by using a material more suited for machining or a more precise AM process that would require less post processing during the fitting phase

Other delays in getting the test series done were the need to design, order of parts for and machining the parts for a new mold body due to the incompatibility of using the CMS mold. These delays were however considered one-time delays, and therefore not considered a bottleneck. The whole process of the first experiment and the time of the different stages are presented in figure 40.

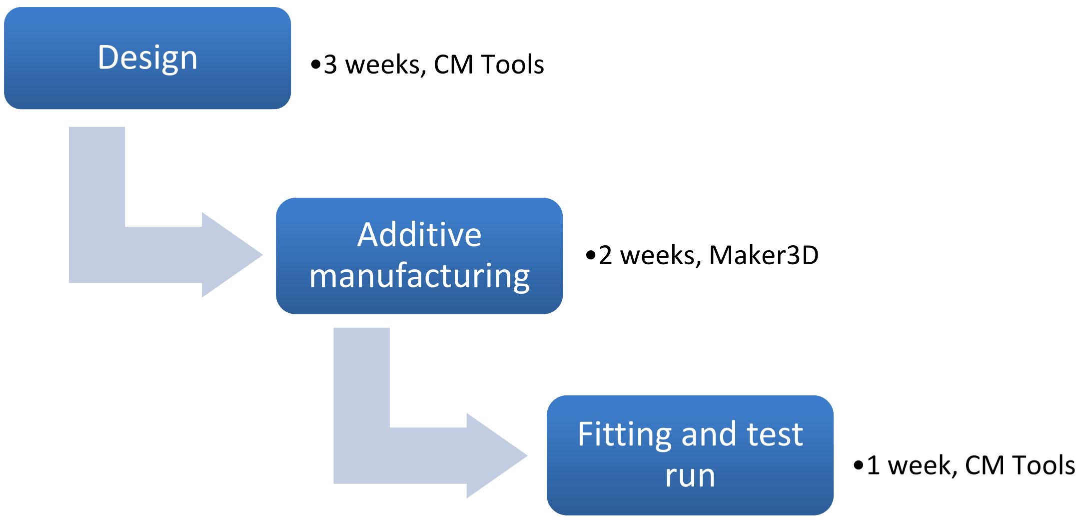


Figure 40. Workflow of the stages involved in producing prototypes, of the production part, with AM IM tools.

4.3.2 Case study 2: Detail design part

In the second case, for evaluating the feasibility of using AM IM tools in the PDP, a part that was in a real development process was used. The part was in the detail design phase, and it was crucial to get functional tests done as well as presenting the product to different stakeholders before going further with the design.

As the part had been designed, two different 3D-printed prototypes were ordered, a SLA model and a SLS model. The SLA model was made from SLA Impact material and the SLS model was made with PA2200 polyamide material. The prototypes were then 3D scanned using an ATOS III Triple scan 3D scanner to assess the dimensional accuracy of the parts. The results were analyzed using GOM Inspect 2016 software. The results of the scan are presented and analyzed in chapter 5.1.2.

However, as the 3D-printed prototypes were neither manufactured out of the accurate material specified for the product nor with the right manufacturing method, standardized tests could not be carried out on these prototypes. Therefore, new prototypes were made using AM IM tools. These prototypes were made from the final material for the product, which meant that proper functional testing could take place.

The same base geometry for the core and cavity inserts, as for the first benchmark experiment, were used. The new part was fitted into the base geometry in the same way as for the first part. However, because the geometry of the new part was more complex than the first part, some modifications needed to be made. Slides were needed to allow for the undercuts to be made and a stepped parting surface was designed to the mold inserts. The slides were designed without a slider subsystem, so that the slides were ejected along with the part and then manually inserted back into the mold insert in between shots and the slides were machined out of steel. One of the slides can be seen in figure 41.

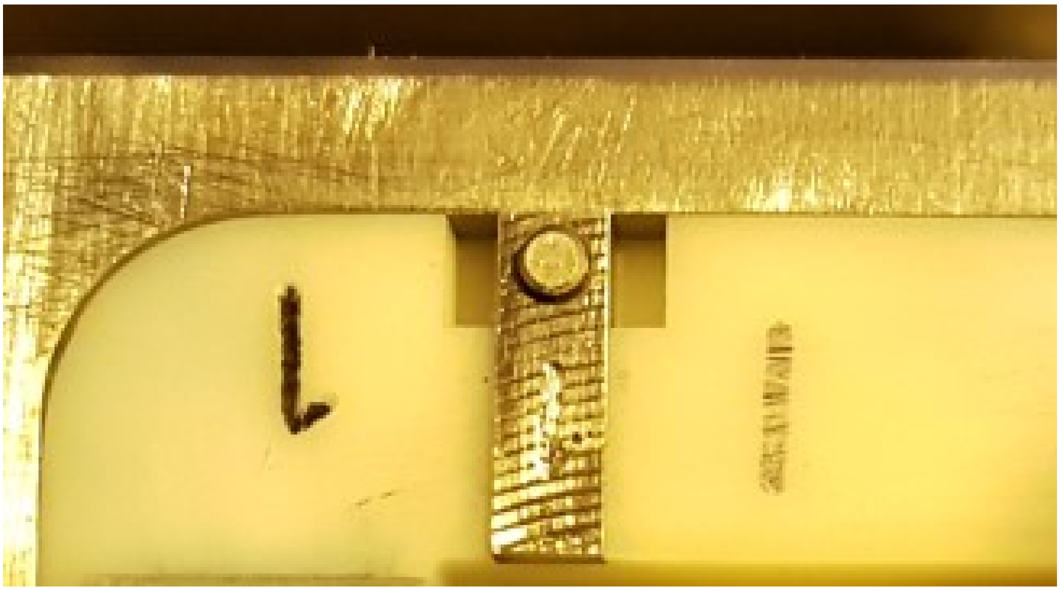


Figure 41. The steel slides were inserted manually into the AM IM insert in between shots.

As it was established in the first experiment, the bottlenecks were the lead time for acquiring the mold inserts and the poor machining qualities of the Accura Bluestone material. Therefore, first mold inserts for this experiment were ordered from the same supplier as in the first experiment but the material was changed to Formlabs High Temp material printed with a Formlabs Form 1 printer. Another set of inserts were ordered from Proto Labs and the material for these were DSM Somos nanotool.

The first test run was done with the inserts manufactured with the Formlabs High Temp material. With these inserts, there were some problems already when fitting them to the mold plates. The inserts were very brittle and a lot of small cracks had formed into the inserts when they were machined and pieces had fallen of. However, as the inserts were intact, and the cracks and missing pieces were concentrated to the outer edges of the insert a test run was conducted with the tools. There was catastrophic failure in both the core and cavity inserts during the first shot with PP as the cavity insert was split in half and parts broke off from the core insert. As a result, the part was only partially filled and could not be used for functional testing. The failure of the insert can be seen in figure 42.

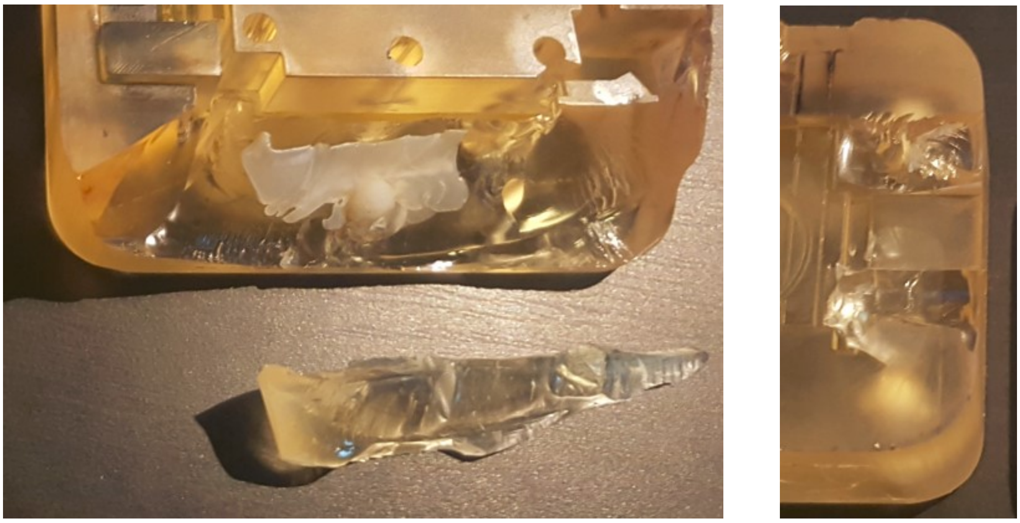


Figure 42. Catastrophic failure of first inserts, manufactured out of Formlabs High Temp resin. The failure happened after only one shot.

The next test was done using the inserts made with DSM Somos nanotool material. These tools were less brittle, and suffered hardly any damage when machined and fitted to the mold plates. However, during the test run, also these tools were broken during the first shot. The failure was not as extensive as for the first inserts, but the failures were at the same locations as in the core insert made with Formlabs High Temp. This fact lead to the conclusion that there was a problem with the design of the cavity insert. The shut off surfaces designed into the cavity insert were too tall and the surfaces were not dimensionally accurate enough, when manufactured with AM technologies, to get a tight fit with the corresponding surfaces on the core insert. To resolve the design issue, aluminium reinforcement inserts were introduced into the problematic areas of the cavity insert. The problematic areas of the core insert can be seen in figure 43.

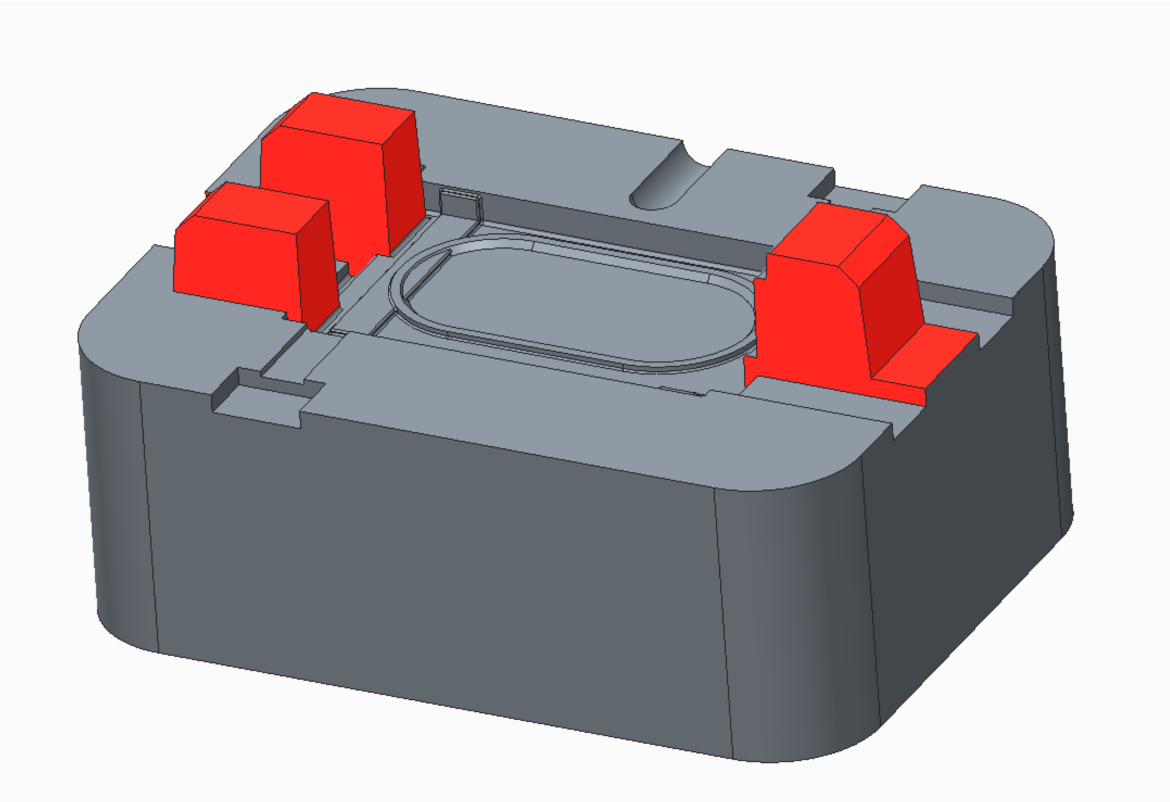


Figure 43. Cavity insert for detail design part prototypes, with problematic structures marked in red.

Another set of inserts made with the DSM Somos nanotool material was used for the next test run, with pockets machined into the cavity insert to allow for the aluminium inserts to be placed into the problematic area. During this test, a total of 15 parts were made with no significant failure to the inserts, other than small cracks in some weak spots of the insert geometry. The machined aluminium insert that was inserted in the problematic area of the cavity insert can be seen in figure 44 and the core insert can be seen in figure 45.

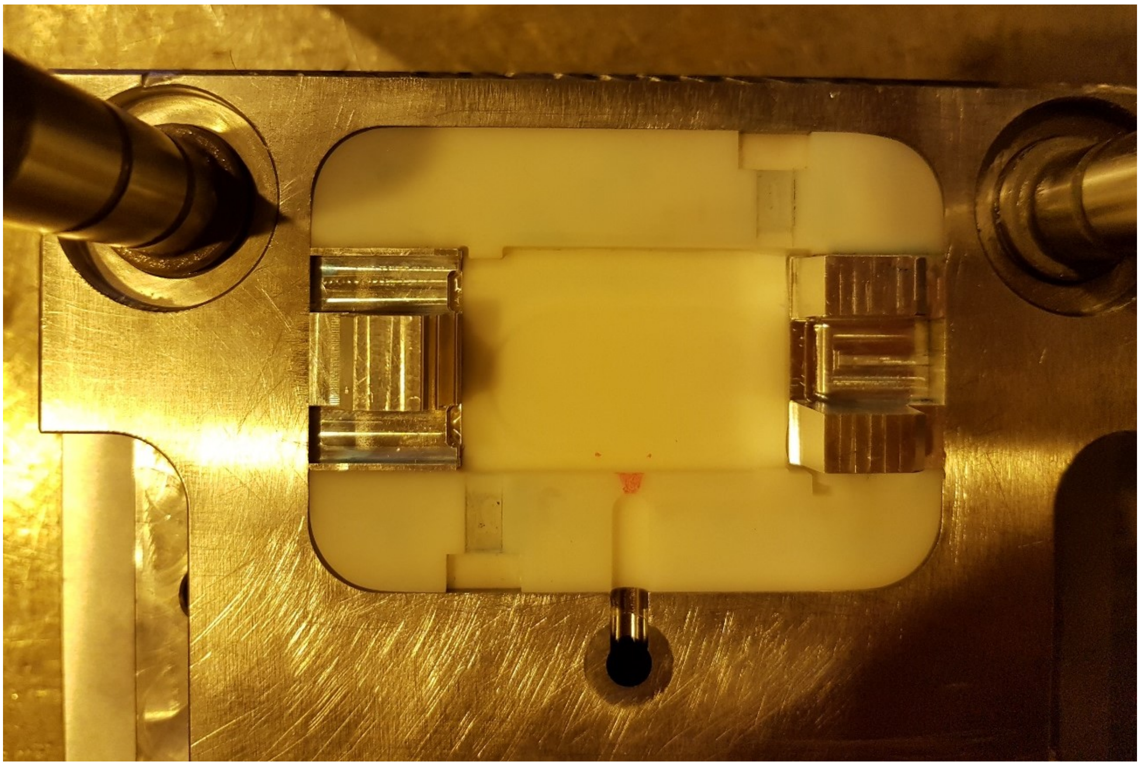


Figure 44. Cavity insert with machined aluminium inserts in problematic shut off areas. No visible damage to the AM insert.

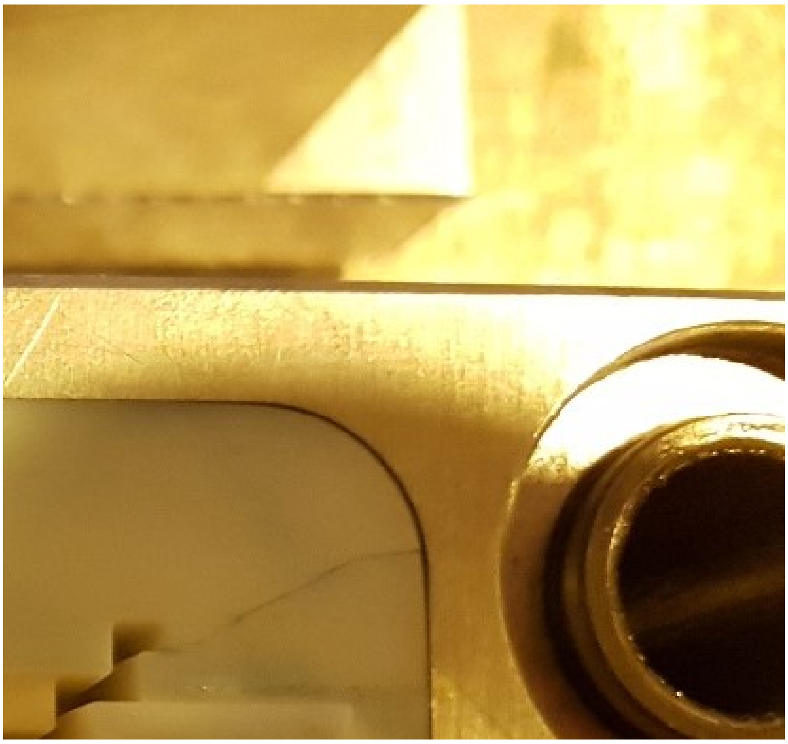


Figure 45. Small cracks visible in the corner of the core insert.

From the test run of 15 parts, one part was chosen randomly from the test batch for 3D scan analysis. The part was scanned using the ATOS II Triple scan 3D scanner and the results were analyzed using the GOM Inspect 2016 software. The 3D scanned geometry data of the injection molded part was compared to the CAD data of the part as well as to the 3D scanned geometry data of the 3D printed SLA model and SLS model of the part. When compared to the CAD model, it is clearly visible that the part is bent inwards along the long sides of the part. This is mainly due to the lack of sufficient holding pressure and adequate cooling of the mold. This was however expected, as simulation of the IM process was done before the implementation. The results and analysis is presented in chapter 5.1.2. The warped edge can be seen in figure 46.

Figure 46. Warpage of the long edges of the injection molded detail design prototype

The ejection of the part from the mold worked quite well. There was however, some issues near the ejector pin closest to the injection gate. When ejected from the mold, there was plastic deformation in the part due to the force that the part was subjected to from the ejector pin. The reasons for this problem is the shrinking of the part around the core, which leads to a need of a higher force for ejecting the part in addition to the lack of tempering in the mold. The area that suffered from deformation also has a thinner wall thickness due to the design of the part and it is close to the gate, which is the hottest spot during the ejection.

The overall lead time for producing prototypes of the detail design part was longer than the lead time for the production part, due to the problems with the braking cavity insert. However, when analyzing the different stages involved in the process, design of the mold inserts, additive manufacturing of the IM tools and fitting to the mold platens, it can be concluded that the process was one week faster than the first test run. The time for designing was roughly the same, as was the time for fitting and test run. The time for additive manufacturing of the IM tools was reduced to one week and therefore the total lead time was five weeks. A visualization of the stages and lead times can be seen in figure 47.

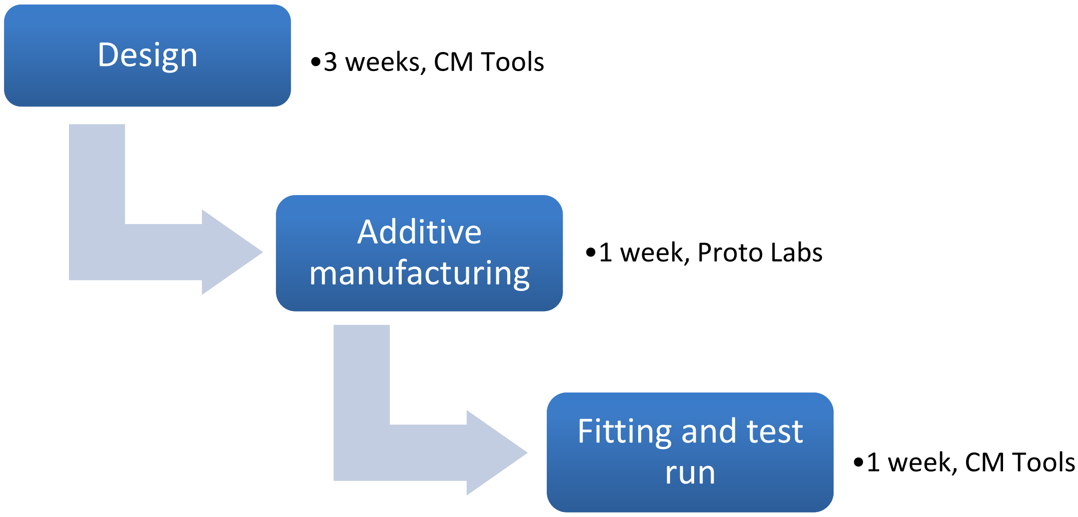


Figure 47. Workflow of the stages involved in producing prototypes, of the detail design part, with IM AM tools.

In addition to studying the possibilities of using AM IM tools for producing the part in the detail design phase, a quotation for an aluminium prototyping mold from Proto Labs was asked for. As Proto Labs are marketing a quick delivery of 15 days or less for 25 – 10 000+ injection molded parts, the quotation was used as a benchmark for producing the mold with traditional methods instead of using AM IM tools (Proto Labs, 2017). The quotation however, included several modifications to the original part, due to the standardized process used to manufacture the prototyping molds at Proto Labs. Therefore, the method of producing a prototyping mold out of aluminium with traditional mold manufacturing methods was discarded. The details of the quotation are classified.

4.3.3 Case study 3: Variation of existing part

The third part used for the practical testing in this study, is a variation of an existing part. The idea was to produce a small series of this part to be able to test the assembly of the new variation of the end product. The testing included the evaluation of the compatibility of using the new variation of the part in the existing automated assembly line.

The geometry of part used in this case study was more complex than the previous parts, and a total of eight smaller inserts needed to be designed into the main mold inserts, four on the core side and four on the cavity side. Two spring loaded slides were also included to take care of the undercuts. Pockets needed to be machined into the mold platens to allow for the slides.

As the idea was to produce a series of over 100 parts for this case study, the possibility of using DMLS manufactured aluminium inserts was conducted. Aluminium was chosen for this test as it has good thermal properties in addition to good hardness, strength and dynamic properties. (EOS, 2017a) Another reason for doing the first test with aluminium DMLS inserts, instead of maraging or stainless steel, was to evaluate the feasibility of aluminium DMLS inserts with minimal post processing, as the given accuracy is lower for aluminium than for the steels.

The inserts were designed based on the geometry of the new part and as the inserts were to be manufactured out of metal instead of plastic, water cooling was added to the mold design. This meant that cooling lines also needed to be machined to both injection mold platens.

The typical achieved part accuracy specified in the data sheet for AlSi10Mg from EOS, which Proto Labs uses, is ±100 µm and the surface roughness as manufactured and cleaned is R_a 6-10 µm. The inserts were manufactured by Proto Labs using an EOS EOSINT M 280 DMLS machine. The EOS EOSINT M 280 has a build volume of 250 mm x 250 mm x 325 mm, it uses a 200W Yb-fiber laser, the focus diameter can be varied between 100 – 500µm and the layer thicknesses can be varied between 20 – 100µm. The machine is marketed to be ideal for making IM tools, by eliminating tool-path generation for conventional IM tool manufacturing and multiple machining processes. (EOS EOSINT M 280 data sheet, 2017; EOS, 2017a) The EOSINT M 280 machine is presented in figure 48.

Figure 48. EOS EOSINT M 280, used for manufacturing the aluminium IM inserts. (EOS EOSINT M 280 data sheet, 2017)

The parts were produced out of AlSi10Mg with a layer thickness of 60µm. The tolerance for the parts manufactured were announced by Proto Labs to be ±0.1 mm or ±0.1%, depending of which is bigger. The surface quality was specified by Proto Labs as 200-400 µm. The rough surface quality and relatively high dimensional tolerance was a concern for producing the inserts with this method, but as one of the main objectives in this study is to evaluate the feasibility of using existing AM technologies for producing IM tools, the inserts were manufactured using this method. The additional inserts were also manufactured with the same process.

The inserts had, as expected, quite a rough surface, but it was decided that they were not to be machined using traditional machining processes, other than the machining needed for fitting the inserts to the mold platens and boring the ejector pin holes. Post-processing the inserts further, would have defied the original objective of studying the feasibility of utilizing AM IM tools into the PDP, as the lead times would then be similar to producing inserts with traditional methods. The surface roughness can be seen in figure 49.

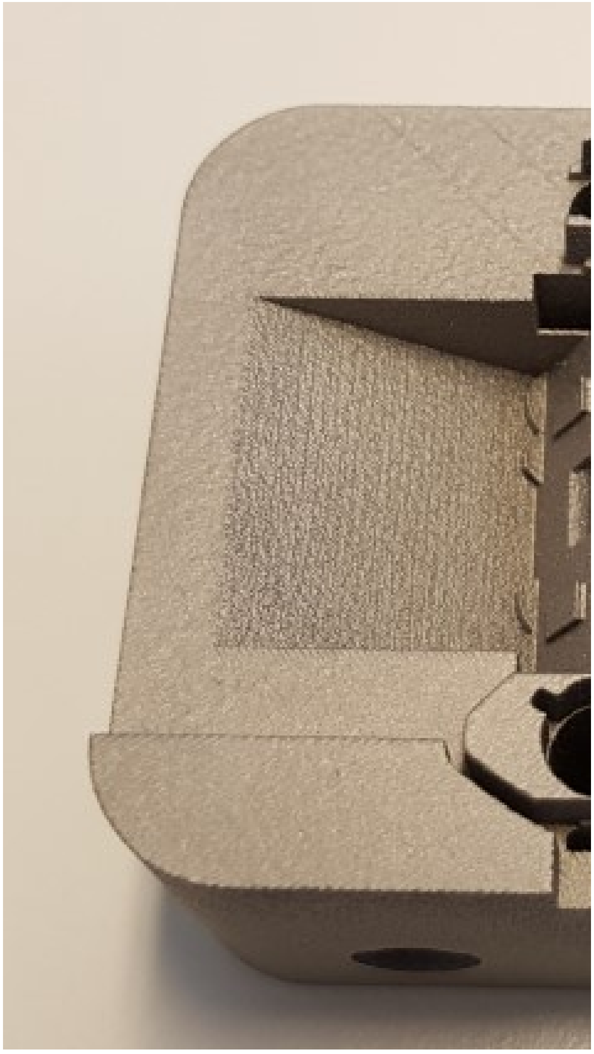


Figure 49. The surface quality of especially the slanted surfaces was very low.

When inspecting the parts produced out of aluminium, it was quickly learned that the smaller inserts were drastically undersized. The diameter of the round pins was around 6.7 mm, while the nominal dimension was supposed to be 7 mm. This deviation in tolerance meant that these inserts could not be fitted to the bigger inserts and used in the test runs. The other set of smaller inserts were as well undersized, and could not be used in the test run. The surface quality was also very low, so concerns were raised that the IM test run would not be successful, due to the risk of the part sticking too much to the mold and plastic pushing through the parting line. It was however, decided that a test run was still to be performed, to evaluate if the inserts could be used, and whether the part would eject from the mold, despite the rough surfaces. For this test, the openings for the smaller inserts were blocked with machined inserts.

The inserts were fitted to the mold platens, the ejector pins were fitted to the core insert and ejection pin holes were machined to the core side platen and the ejector retainer plate. As this test was only done to determine whether the inserts could be used, the modeled slider pockets and cooling channels were not machined into the mold platens.

The first test shot of the aluminium AM IM tools resulted in a part that got stuck to the cavity side of the mold and the part broke into several pieces when the mold was opened. No plastic was stuck on the core insert during the test run.

The disassembled mold, with the plastic still stuck to the cavity insert, can be seen in figure 50. It was also discovered that some thin areas of the cavity insert had been damaged during the test run. The damaged area of the cavity insert can be seen in figure 51.

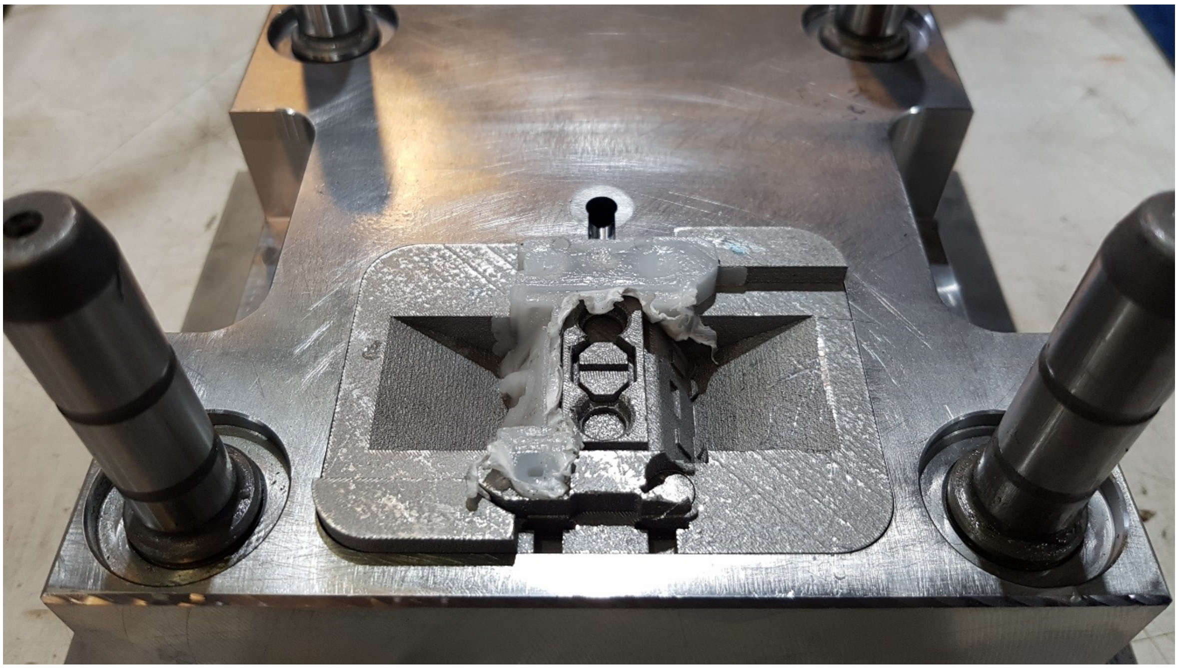


Figure 50. The cavity insert after the test run, with broken off plastic stuck to the surface

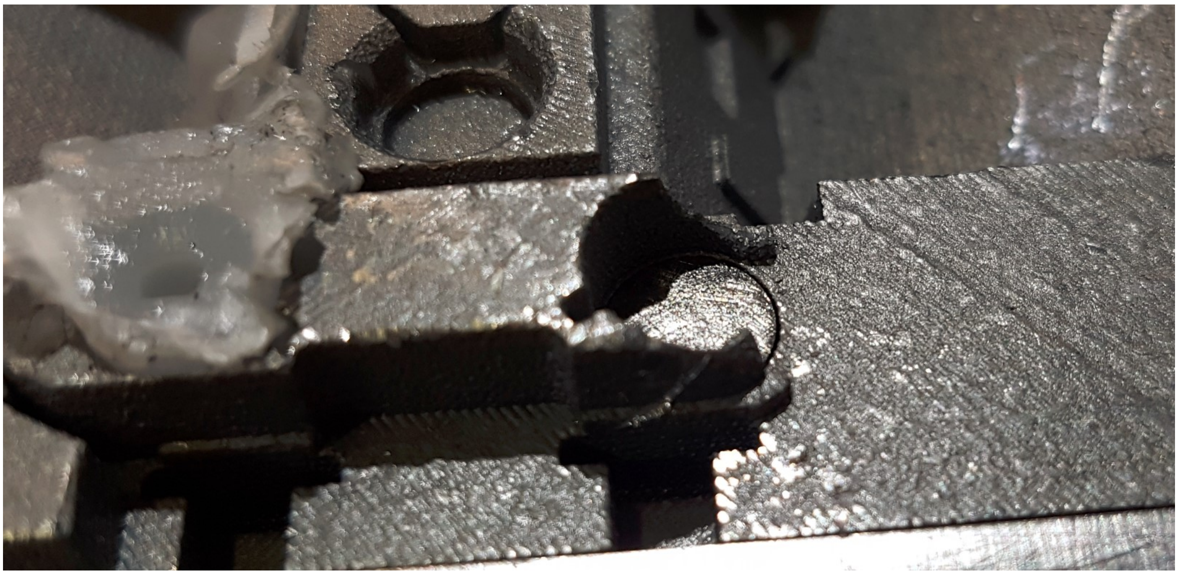


Figure 51. The cavity insert was damaged during the test run of the aluminium AM IM tools

Based on this result, it was concluded that these inserts could not be used for producing prototypes.

Although the experiment with the aluminium inserts failed, the DMLS process has been used for producing AM IM tools in previous research and therefore the study was continued by producing samples and analyzing the accuracy of these samples. The experiment with a complete new set of inserts was not carried out due to time restrictions. Instead, to evaluate the feasibility of using DMLS for producing AM IM tools, two other materials were evaluated by ordering only the smaller inserts, out of maraging steel and stainless steel. For the maraging steel, the layer thickness was 50 µm and it was printed with the EOS EOSINT M 280 machine. According to the datasheet, typical achievable part accuracy is ±20 µm, for parts under 80 x 80mm. A surface roughness of R_a 9 µm, as manufactured, is specified in the data sheet. (EOS, 2017b)

The stainless steel insert was manufactured out of stainless steel 316L. For this part, Proto Labs specified a layer thickness of 20µm. According to the data sheet, the typical achievable part accuracy is ±20-50 µm and a surface roughness of R_a 13 ±5 µm, as machined, for this material. (EOS, 2017c) The part was printed using and EOS EOSINT M 100 machine, which is a DMLS machine with a build volume of Ø100 mm x 95 mm, it uses a 200W Yb-fiber laser and the focus diameter is set to 40µm. The layer thickness is not disclosed on the data sheet. (EOS, 2017d) The EOS EOSINT M 100 is presented in figure 52.

Figure 52. EOS EOSINT M 100, used to manufacture the test insert out of stainless steel with DMLS technology. (EOS, 2017d)

The three inserts produced to evaluate the different materials can be seen in figure 53. The insert to the left is printed out of aluminium, the insert in the middle is printed out of tool steel and the insert to the right is printed out of stainless steel.

Figure 53. DMLS inserts for quality evaluation, aluminium to the left, tools steel in the middle and stainless steel to the right.

4.4 Incorporating AM IM tools into the PDP

The product development process can be divided into six main phases, as presented in chapter 3 of this study. These different phases bring forth different needs for different functions in a company. In this chapter, the different needs of the functions involved in the PDP at ABB WA are addressed and the study whether these needs can be satisfied by producing prototypes is evaluated. The introduction of prototypes manufactured by injection molding is in focus however, the use of different kind of prototypes are also discussed.

The study of incorporating the use of AM IM tools into the PDP was done on the assumption that the six main phases of the PDP are followed during the PDP at ABB WA. Employees of the company were interviewed, to develop an understanding of the current methods used in the different phases of the product development process.

Utilization of AM IM tools in the PDP at ABB WA

Based on discussions at ABB WA, it can be concluded that the main benefits of utilizing AM IM tools, can be found in prototyping. Prototypes are used at different phases and for different purposes during the PDP at ABB WA. To find out where IM prototypes could be beneficial, the case studies describes in chapter 3 were used as a base for evaluating the benefits of using AM IM tools in the PDP used at ABB WA. This was done by becoming familiar with the processes used at ABB WA and making a model for prototype utilization based on the results. The model is presented at the end of this chapter.

The current practice of using prototypes and the needs for prototyping in the PDP at ABB WA was evaluated by interviewing members of the R&D team. The conclusion from these interviews were that 3D printed prototypes are used on average five to six times a year, in some projects more extensively. The quality of the 3D printed prototypes used at the moment are mostly good enough for the intended purpose, although the material qualities are not sufficient for all testing purposes. The testing that cannot be done sufficiently with the 3D printed prototypes include functional testing such as snap-fit testing and standardized certification tests such as temperature testing.

It was also determined that there is no systematic planning for prototyping and the prototypes are typically ordered ex tempore during the process for different cases. It was estimated that half of the prototypes used currently are used for customer feedback and communication and the other half for functional testing.

The IM process was pretty well known at the R&D department and IM process simulations are used in during the PDP of IM parts. Actual design of mold inserts was however not that familiar, and it was determined that it would be better to outsource the mold design process, if AM IM tools were to be utilized at ABB WA. When benchmarking the experience of utilizing AM IM tools in the PDP before this study, the conclusion was that research on the topic has not been done at ABB WA before, although it has been discussed. Evaluating the expectations on possibilities and restrictions for using AM IM tools to produce prototypes, the conjecture was that it could probably be used for simple parts however, there was concerns about warpage due to limited cooling and holding pressure possibilities.

The easiest way to examine the use of prototypes was to start the analysis based on the stage-gate model used at ABB WA, and describing the stages with the help of the generic product development process presented in chapter 3.1.

As the main categories in the stage-gate model involve all the functions needed in the PDP, a simplified representation of the gate model can be used to represent the stages of the PDP where prototypes might be beneficial to use. For this study, the generic PDP by Ulrich & Eppinger (2012), described in chapter 3.1, will be used to identify the needs at the different phases throughout the process. These phases are:

- Planning
- Concept development
- System-level design
- Detail design
- Testing and refinement
- Production ramp-up

To improve the PDP by utilizing AM IM tools, the needs and benefits of using this proposed method was evaluated separately for each of the phases presented above. Interviews were conducted to benchmark the current use of prototypes, as well as the need for new ways of utilizing prototypes, in different functions at ABB WA. The actual stage-gate model used at ABB WA is more comprehensive than the one described below, as it is analyzed in this study only out of the prototyping need perspective.

Starting from the planning phase, also known as pre-Gate 0 stage at ABB WA. At this stage, the customer needs are evaluated and product ideas are gathered to a list. In other words, the product platform and architecture are assessed, according to the generic PDP by Ulrich & Eppinger (2012). At this stage, very few or no physical prototypes are made. Visual representations might be made for some ideas to use as communication tools to different functions inside the company, and in some rare cases simple physical prototypes might be built for the same intensions.

At the next stage relevant to this study, which is actually stage 2 in the stage-gate model at ABB WA, the concept development phase from the generic PDP is carried out. The preceding stage 1 at ABB WA contain project planning segments, which means that there is usually no need for prototypes of any sort at this stage. During the concept development phase, the product is starting to take shape and design models and prototypes are usually developed at ABB WA. Depending on the product, early functional prototypes might be made already at this phase, to test specific functions that might play a big role in the final design of the product. Also, customer involvement is present already at this point of the PDP. System-level design, which is part of stage 3 at ABB WA, is as described in chapter 3.1 the phase when the product architecture is developed and plans for production systems and assembly are done. At ABB WA this means that the product should be developed so far that the production systems can be defined and acquired. At this stage prototypes might come into place for testing that the assemblies and functions work as intended. At this stage at ABB WA, the specification for the products are also completed, which can be seen as the equivalent of the detail design phase in the generic PDP.

In the detail design phase, the final materials are chosen for the products and therefore the testing of prototypes out of the final material might be needed. Also, the tools for manufacturing are designed at this phase, which means that there is a need for assessment of the production process through simulations and prototypes.

At gate 3, the decision for production is made and the process leading to production ramp-up is started in stage 3. This stage can be compared to testing and refinement in the generic PDP presented in chapter 3.1 of this study. At this stage, the production test runs are performed with the production equipment and the final products are tested. Necessary last modifications to the products are done and the required product certificates are acquired. AM IM tools could be beneficial in some cases for producing parts for the certification process or other functional testing, where the intended modifications to the production tools include significant risks.

At stage 4, the production ramp-up is done. The process at ABB WA is very similar to the process described in chapter 3.1, where possible problems with the production tools are sorted out and the workforce is trained. At this phase, results from test installations are also analyzed by the product developers at ABB WA. At this point the AM IM tools could be used to test possible improvement suggestions from the test installations, to see whether it would be beneficial to make some late modifications or not.

Stages 5 to 7 include the launch of the product and product lifecycle management phases which are not addressed in this study, as these phases do not involve a need for prototypes.

A representation of the PDP at ABB WA and the equivalent phases in the PDP described in the literature study in chapter 3.1 is presented in figure 54.

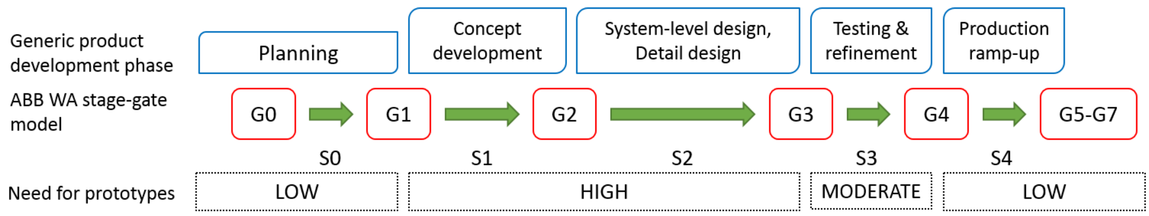


Figure 54. The stage-gate process at ABB WA, with corresponding phases in the generic PDP and the need for prototypes at each stage

Based on the analysis of the PDP at ABB WA and the gathered information in this study, both through literature studies and through case studies involving practical implementations and interviews, a process for evaluating the possible utilization of AM IM tools in the PDP can be developed. The process would be added to the existing PDP at ABB WA, as three different phases:

- Identification and planning
- Manufacturing and testing
- Analysis and documentation

The identification and planning phase would consist of characterizing the product that will be developed, planning for the prototyping needs and testing and evaluating different methods and materials for the prototypes at different stages of the process. By characterizing the product by the categories described in chapter 3.1, determining the different needs for prototyping and testing will be easier, as the documentation and learnings from earlier prototyping processes will provide a basis for future projects. By identifying the testing needs early in the process, the decision of utilizing of AM IM tools can be made and resource planning can begin. As the needs for prototyping and testing has been determined, prototyping milestones should be set. The milestones should be based on the needs identified in the identification and planning phase, and resources for the planned manufacturing and testing should be allocated. 3D printed prototypes require less resource allocation, but if there is a need to produce prototypes with AM IM tools, the resource demand is substantially higher. Based on the practical implementation of this study, resource management and planning has a big influence on the lead time for prototyping with AM IM tools. As the testing can in this context be functional testing, customer feedback or other communication, resource allocation can reduce both lead time and costs as prototypes can be ordered for different projects at the same time, if the milestone schedules match. Testing should be carried out according to the goals set in the planning phase and results should be analyzed and documented. Systematic analysis and documentation of the prototype testing results can improve the learning process of the teams involved in the PDP, as the information is shared with a wider audience.

As the PDP usually consists of several iterations of the different phases, the prototyping process is also an iterative process, where the different phases are repeated and revised as the project moves forward. A visualization of the PDP, with the added prototyping process, can be seen in figure 55.

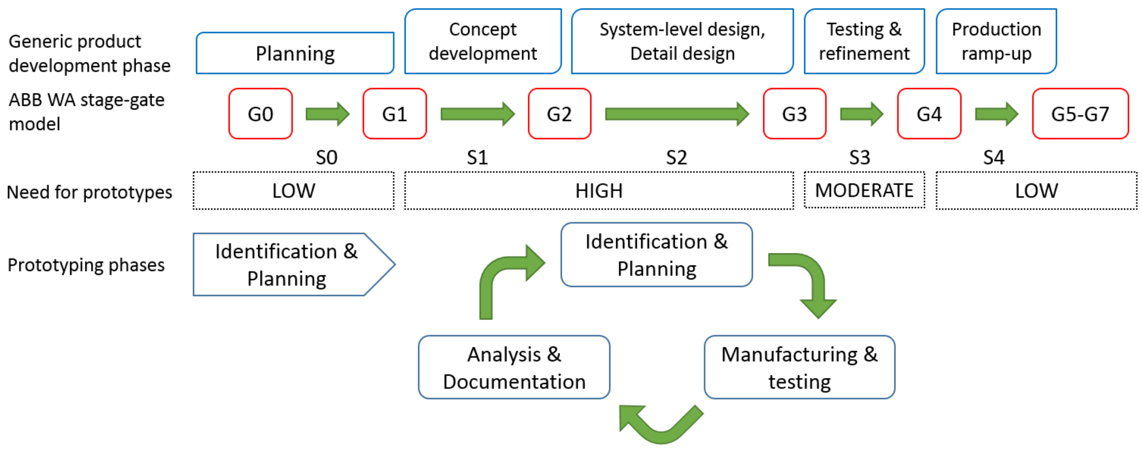


Figure 55. Product development process with systematic prototyping process included

4.5 Evaluation criteria

Evaluation of the technical feasibility of utilizing AM IM tools, was based on the ability to produce decent parts without failure of the tools, measurements of the parts as well as functional testing of the prototypes. By changing process parameters during the IM process, the impact on the tools and the parts could be evaluated. As the holding pressure profiles were changed in the first test, the impact of decreased warpage versus increased flashing, could be evaluated. It should however, be pointed out that other factors might affect the outcome, such as degradation, heating and cracking of the tools. These factors are hard to control, especially for the plastic AM IM tools.

The AM IM prototypes were also compared to the 3D printed prototypes, both by dimensional accuracy but also through functional testing. By conducting functional testing, the materials impact on the functionality can be evaluated better than with the 3D printed prototypes however, as the functional testing is done by individuals, the results might be prone to subjective thinking. To evaluate the technological feasibility of utilizing IM AM tools, the individuals were therefore asked to overlook small errors on the parts, such as flashing, as the parts were still prototypes and small adjustments can be done to the prototypes before testing or showing them to different stakeholders.

5 Results and analysis

In this chapter, the learnings and measurements from the tests will be presented and analyzed and an evaluation of using AM IM tools to produce prototypes compared to other prototyping methods, with a focus on shortening the lead time for the whole PDP and for testing the functional properties of the products is presented and analyzed. The analysis is based on learnings from the literature study on product development, injection molding and additive manufacturing as well as the results gained from the case studies and interviews. In chapter 5.1 the technical results from the experiments will be introduced. The results from each case study is presented in sections 5.1.1 – 5.1.3. In chapter 5.2 the evaluation of using AM IM tools in the PDP is reviewed based on the needed resources to achieve the prototypes and benefits to the overall PDP.

5.1 Technical evaluation of the practical implementation

During the test runs of three different products, both data about the inserts and the final prototypes was collected through different methods. The inserts themselves were inspected only visually for significant wear or structural failure, as the main focus of analysis was on evaluating the prototypes. The prototypes were analyzed using 3D scanning and video measurement equipment, as well as through functional testing by assembling the prototypes with the other parts in the assembly. The quality of the measurements done with the 3D scanning equipment was very good and there was no major issues with getting reliable 3D models of the final prototypes. The very precise results showed both the dimensional accuracy, the warpage as well as the flashes that were present on the prototypes. With the video measurement equipment, the main dimensions could be measured for a larger amount of samples more effectively than with the 3D scanner. For the functional testing part, the parts were only used for assembly testing as well as for showing the progress to different stakeholders, including customers. There were therefore no further structural tests done, to compare the injection molded prototypes with 3D printed prototypes.

5.1.1 Results and analysis of the production part

The production part, which was used for benchmarking the AM IM process, was measured in a similar way as the actual production part is measured for quality assurance. Four main dimensions, with the actual tolerances specified for production, was chosen as inspection dimensions for evaluating the performance of the AM IM tool produced for the first case study. The four dimensions that were measured can be seen in figure 56.

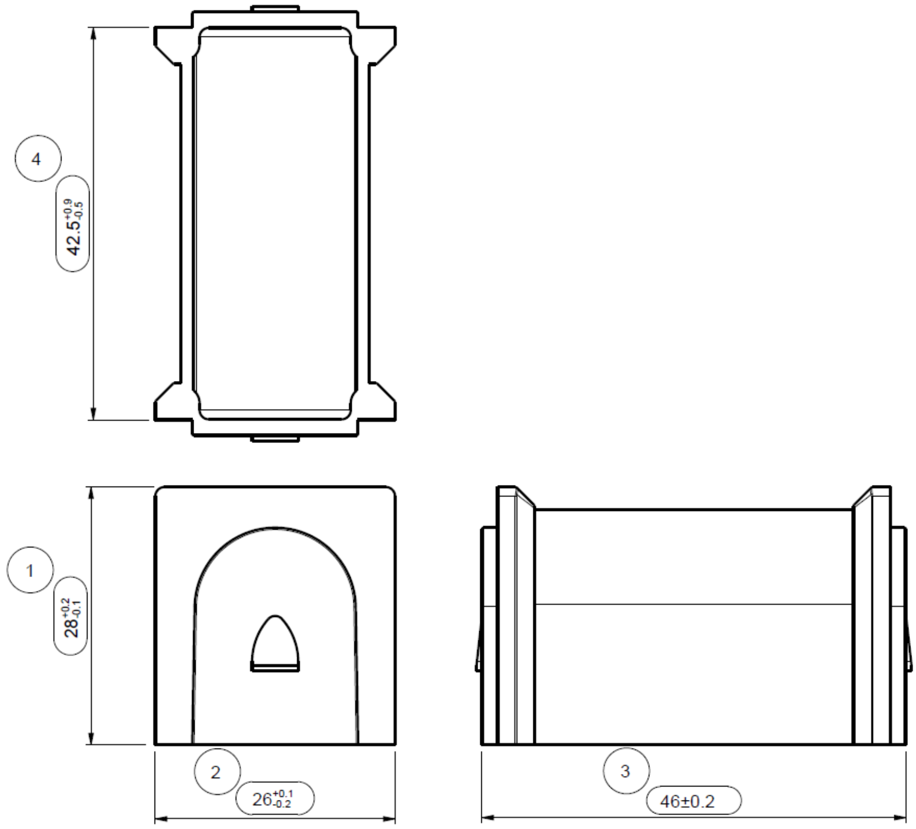


Figure 56. Inspection dimensions for production part prototype.

Video measurement equipment was used to determine the quality of the production part prototypes. The video measurement equipment used, was a Nikon VMR-3020 device. The measurement setup and device can be seen in figure 57.

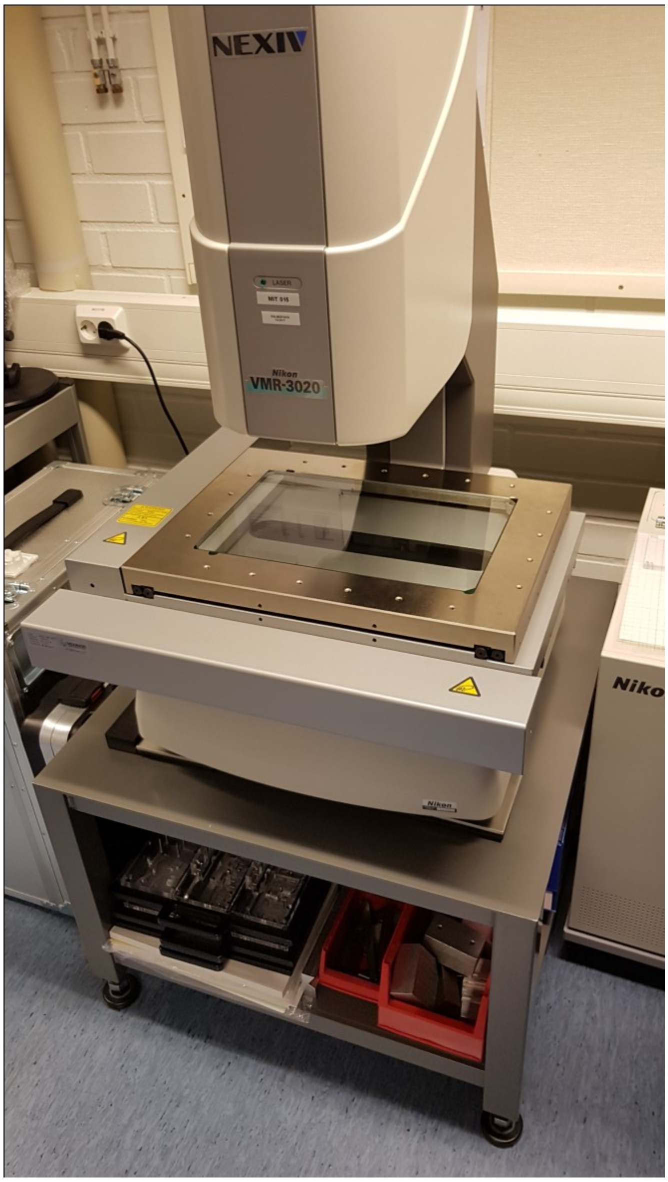


Figure 57. Nikon VMR-3020 video measurement device used for measuring the production part prototypes.

As there were four different holding pressure profiles used in the test, three samples out of every parameter set was measured. The distribution of the dimensions can be seen in figures 58-62.

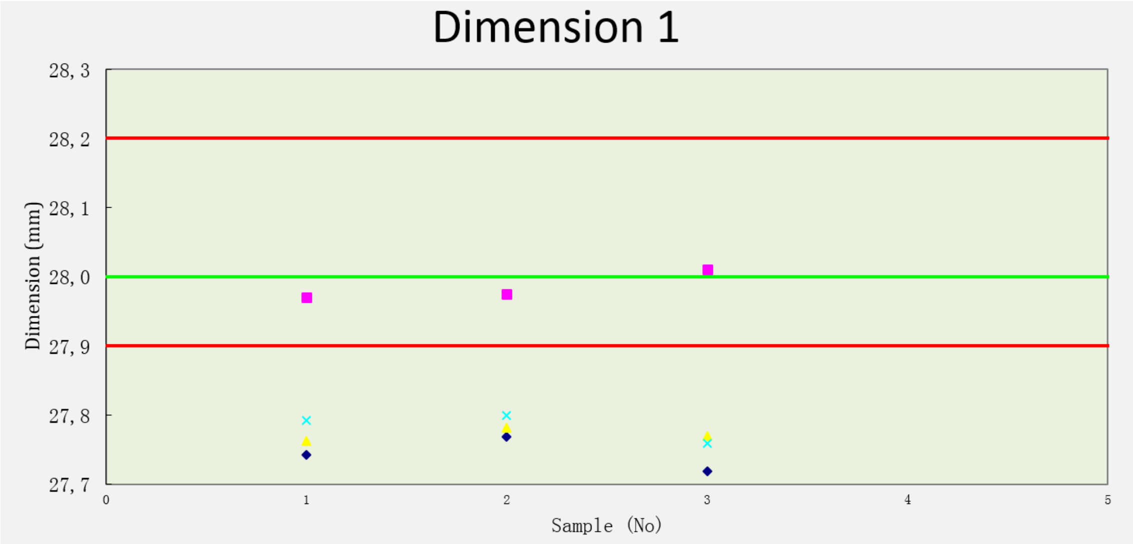


Figure 58. Scatter diagram of dimension 1, with parameter A series represented with blue diamond, parameter B series with purple rectangle, parameter C series with yellow triangle and parameter D series with cyan cross.

When examining the results from dimension 1, it can be concluded that only sample series B are inside the specified tolerance area. As the other results are significantly different, this result suggests that the parts from parameter series B might have been measured in another way than the other sample series. The other samples, although they are below the lower tolerance, the dimensions are quite consistant. The consistancy in dimensions from nine samples (three each from parameter series A, C and D) show that it is possible to get stable results from the AM IM tool made out of Accura Bluestone material.

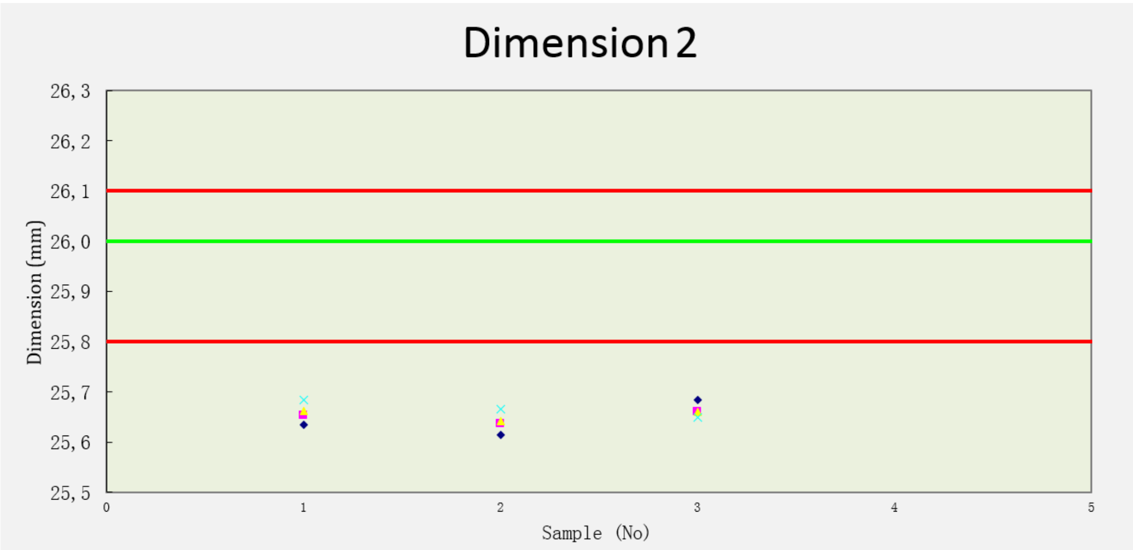


Figure 59. Scatter diagram of dimension 2, with parameter A series represented with blue diamond, parameter B series with purple rectangle, parameter C series with yellow triangle and parameter D series with cyan cross.

For dimension 2, all the samples were under the specified lower tolerance, but as with dimension 1, the variation between samples was very small. This suggests again that the molding process was quite stable.

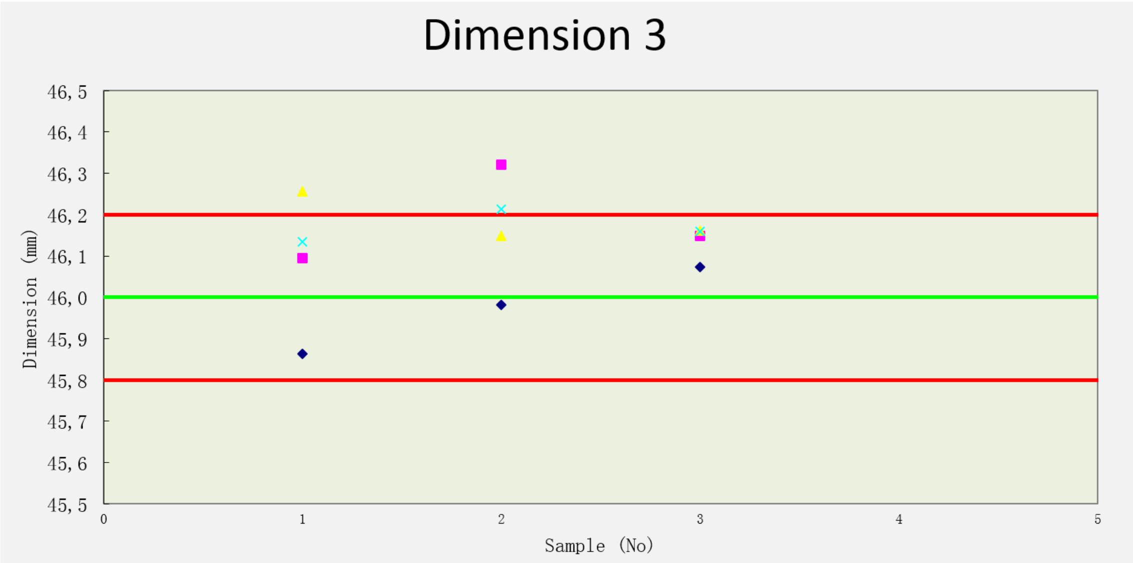


Figure 60. Scatter diagram of dimension 3, with parameter A series represented with blue diamond, parameter B series with purple rectangle, parameter C series with yellow triangle and parameter D series with cyan cross.

Analyzing dimension 3, it is clear that there is significantly more variation between the samples. The variation is present between the different parameter series, but also for the samples from the same parameter set. Most of the dimensions are inside the specified tolerance interval. By rearranging the dimensions in the scatter diagram, so that they are arranged from smallest to largest dimension, it is clearly visible that parameter series A differs significantly from the other parameter series. A conclusion can be drawn that the increase in holding pressure time increases this dimension, as can be seen from the jump in the dimension between parameters series A compared to the other parameter series, while the changing of the holding pressure profile does not seem to have an impact on the dimension. This conclusion should however be made with caution, as the number of samples used for this analysis was small, with only three samples per parameter set. The rearranged scatter diagram for dimension 3 can be seen in figure 60.

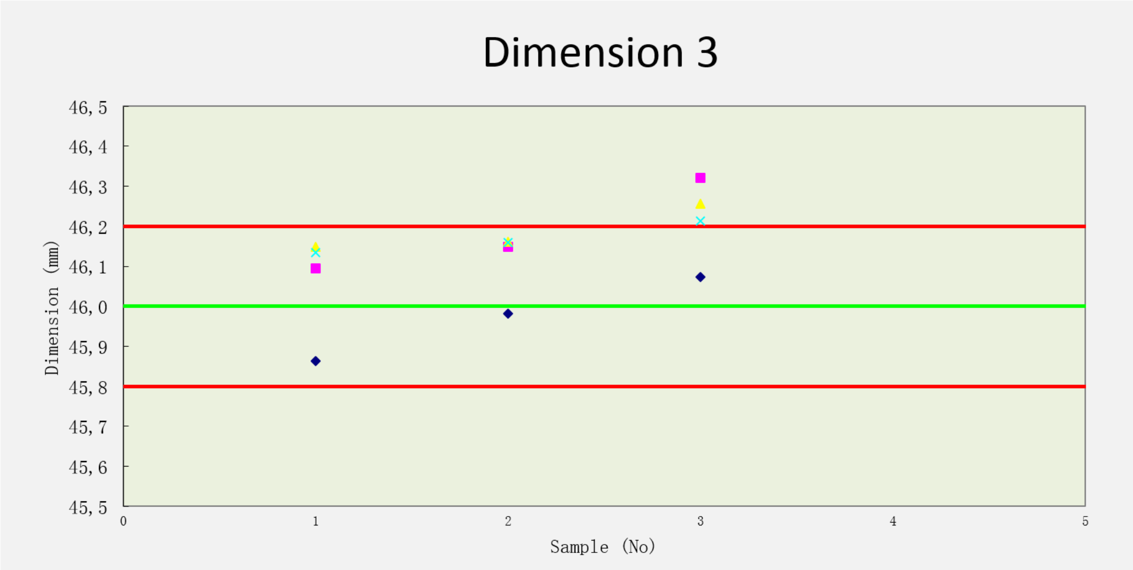


Figure 61. Rearranged scatter diagram, for dimension 3, that suggests that this dimension increased with the increasing of holding pressure time, while the holding pressure profile does not seem to have an impact on the dimension.

Due to some variation between the dimensions in the different parameter sets, the scatter diagram for dimension 4 was also rearranged from lowest to highest values. The diagram shows a jump first from parameter series A, to parameter series B and C. Parameter series B and C show quite similar results, while a significant jump happens between parameter series C and D. This result suggests that the increase of holding pressure has a bigger impact on dimension 4 than the increase of holding pressure time. The results should however be evaluated with caution as the amount of samples were small, three samples per parameter set, and parameters such as mold insert temperature and tool wear were not measured in between shots.

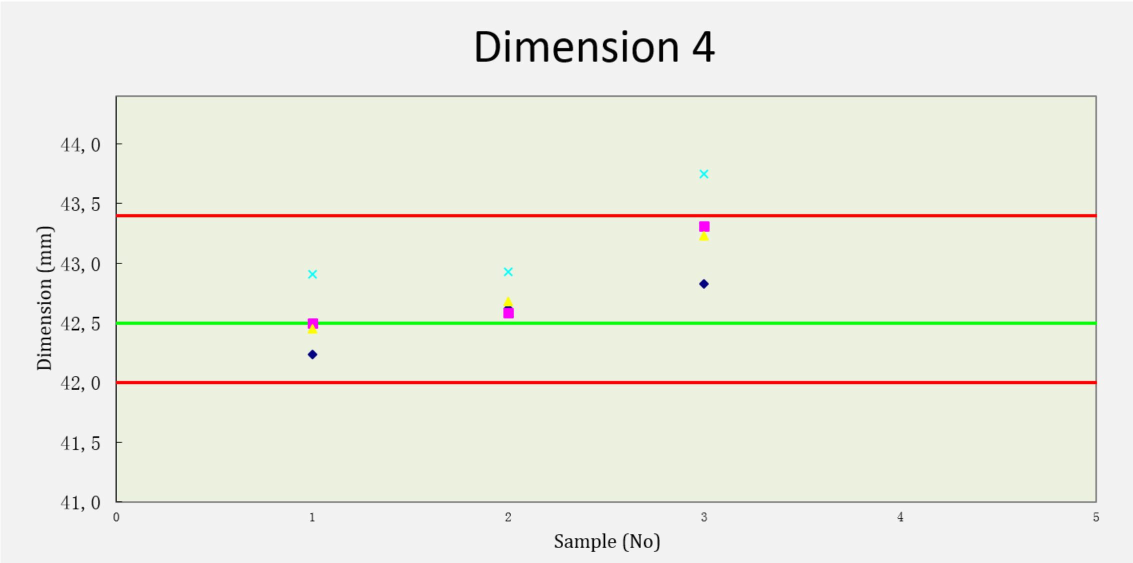


Figure 62. Rearranged scatter diagram of dimension 4, with parameter A series represented with blue diamond, parameter B series with purple rectangle, parameter C series with yellow triangle and parameter D series with cyan cross.

From the results gathered in this section, it can be concluded that for a simple part produced with AM IM tools manufactured out of Accura Bluestone material, it is possible to produce a small series of prototypes with a dimensional accuracy similar to production parts.

5.1.2 Results and analysis of the detail design part

The detail design part was evaluated by comparing 3D printed parts, manufactured with SL and by SLS technologies, with parts produced with AM IM tools. The main comparison was done by 3D scanning the different prototypes and the equipment used for the 3D scanning was an Atos III Triple Scan 3D scanner. The scanning setup can be seen in figure 63.

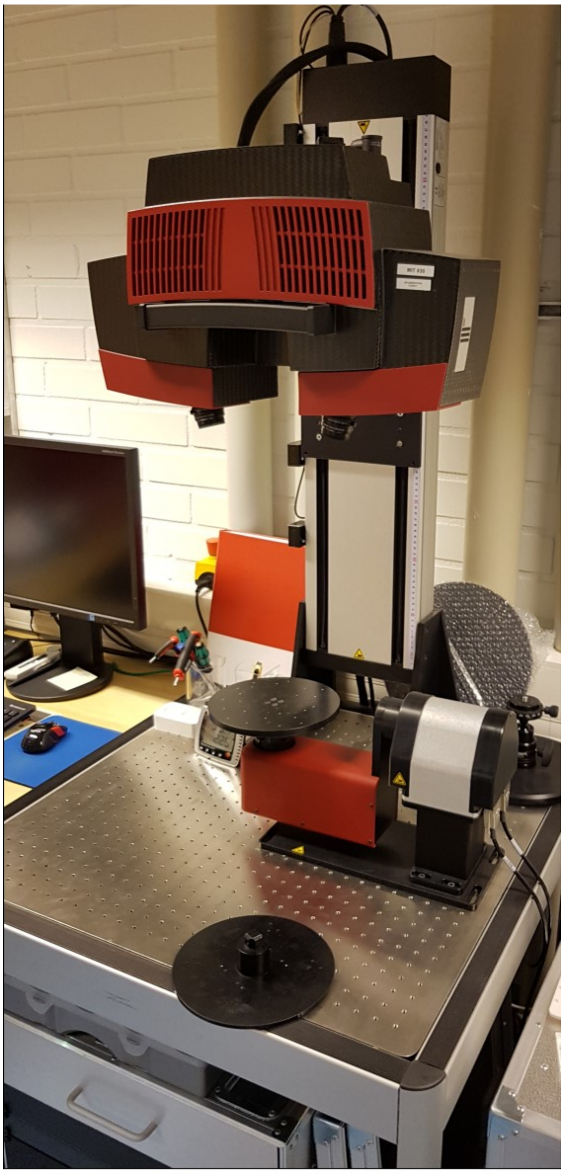


Figure 63. ATOS III Triple scan 3D scanner used for evaluating the detail design part prototypes and variation of existing part inserts.

First the SL and SLS models were 3D scanned and compared to the 3D CAD model using GOM Inspect 2016 software. When examining the results, it is clear that there was significant deviation in the dimensions of the SLS part. A snapshot of the areas with the largest deviations can be seen in figure 64. The green color of the color scale represents no deviation from the nominal dimensions, while blue represents negative deviation and red positive deviation from the nominal value.

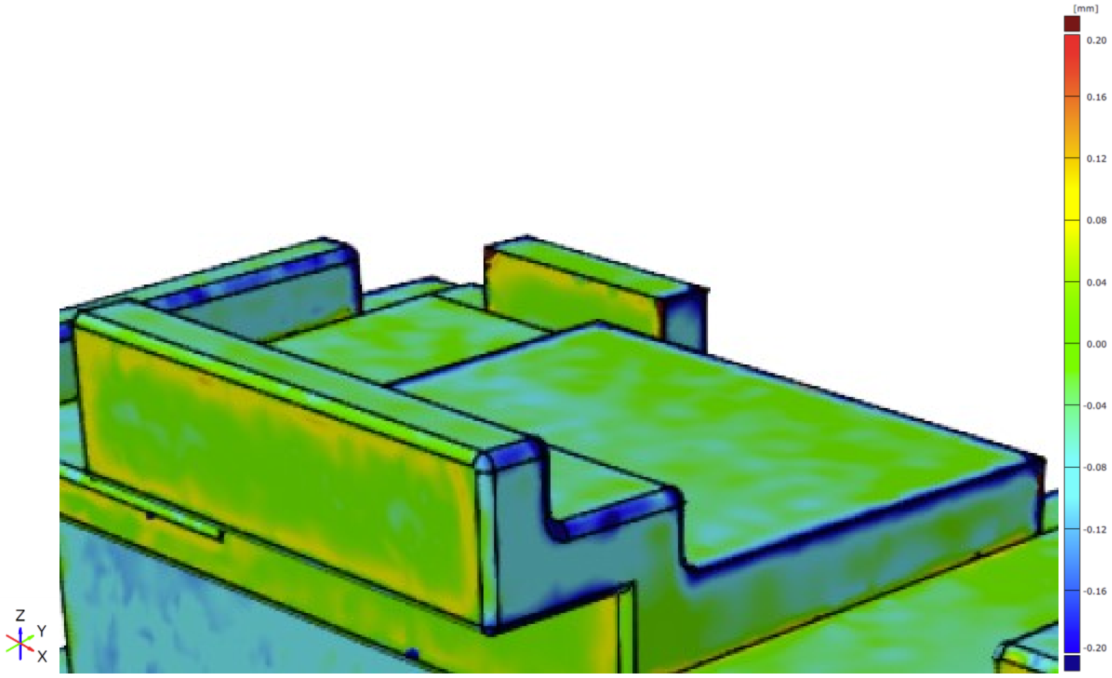


Figure 64. 3D analysis of the SLS part with a focus on the areas with the largest dimensional deviations.

When looking at the same area of the part manufactured with SL technology, it is clear that the dimensional accuracy is substantially better, with only minor deviations from the nominal values. The 3D analysis of the SL part can be seen in figure 65.

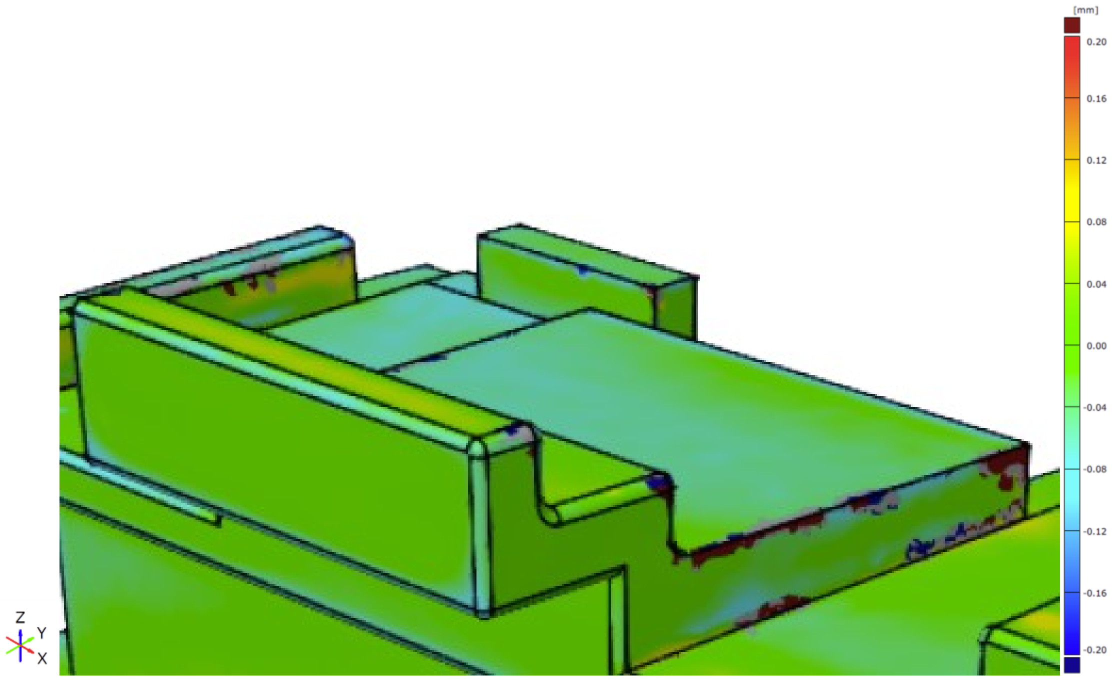


Figure 65. 3D analysis of SL part with a focus on the areas with the largest deviations.

The same analysis was done to the part manufactured with AM IM tools. In the analysis, it is visible that there is significant deviation from the nominal geometry represented by the CAD geometry. This is mainly due to the warpage which occurs because of the uneven shrinkage in the part. It should also be noted that the geometry was changed between the stages of analyzing the 3D printed parts and the injection molded part. However, the main features are still present in both models, and the accuracy of these can therefore be compared. The 3D analysis of the corresponding is of the injection molded prototype can be seen in figure 66.

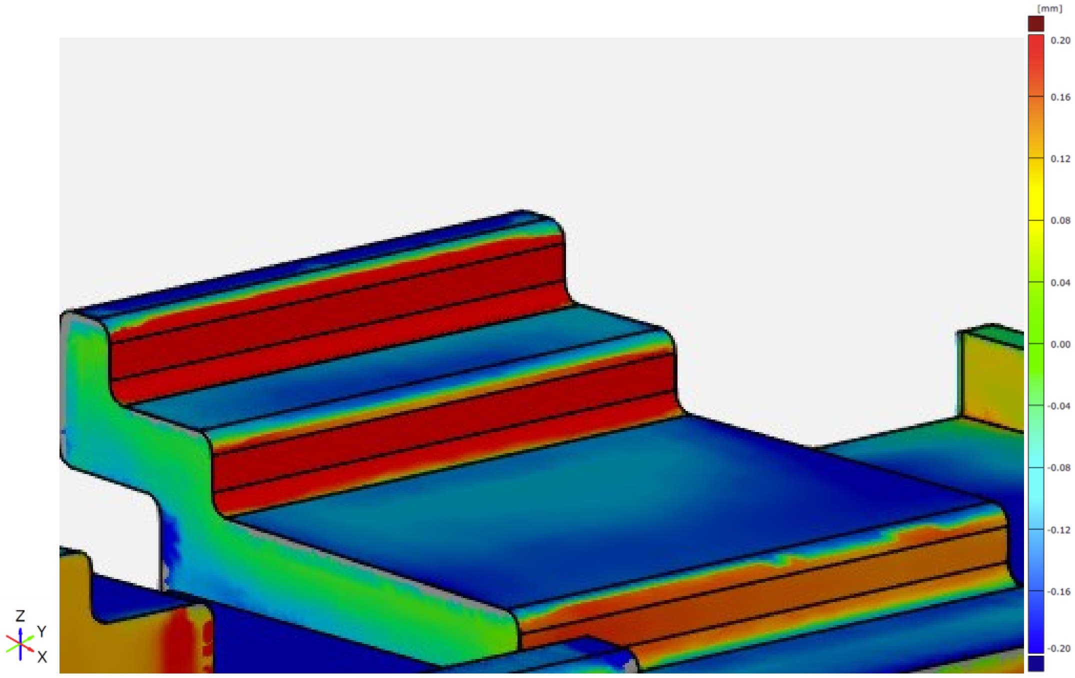


Figure 66. 3D analysis of the injection molded prototype with a focus on the areas with the largest deviations.

5.1.3 Results and analysis of variation of existing part

As concluded in chapter 4.3.3, the quality of the aluminium DMLS inserts were not good enough for direct utilization in the IM process. As the DMLS technology is such a viable method of producing IM tools with, some measurements were carried out, despite the failed utilization during the practical implementation.

To determine the accuracy of different DMLS materials, the smaller inserts designed for the AM IM tool were analyzed through 3D scanning. As can be seen in figures 67, 68 and 69, there is significant dimensional deviation in both the aluminium insert and the tool steel insert. The insert manufactured out of stainless steel is however considerably better quality, aside from the top, which is drastically under dimensioned. The deviation, visualized as a dark blue area in figure 69, is most likely due to a disruption in the manufacturing process.

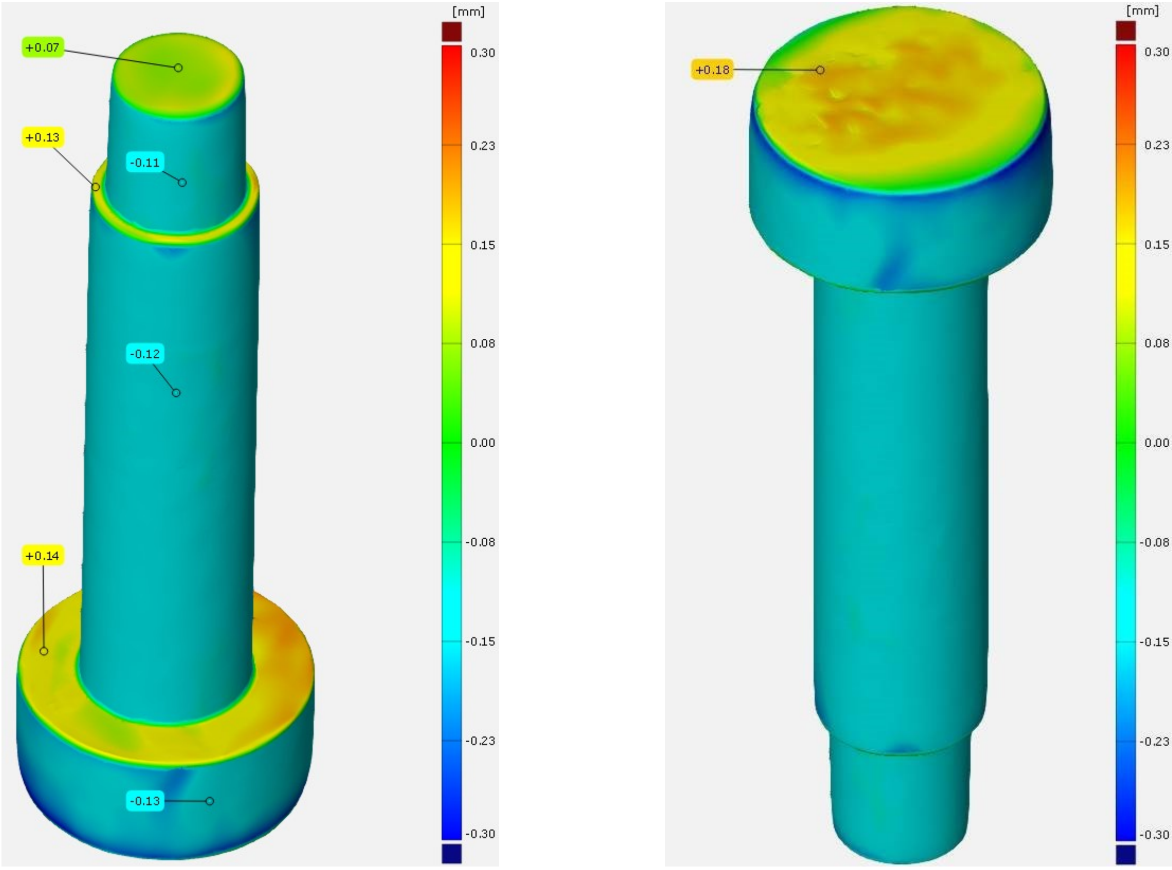


Figure 67. Aluminium DMLS insert, significant deviation from nominal dimensions.

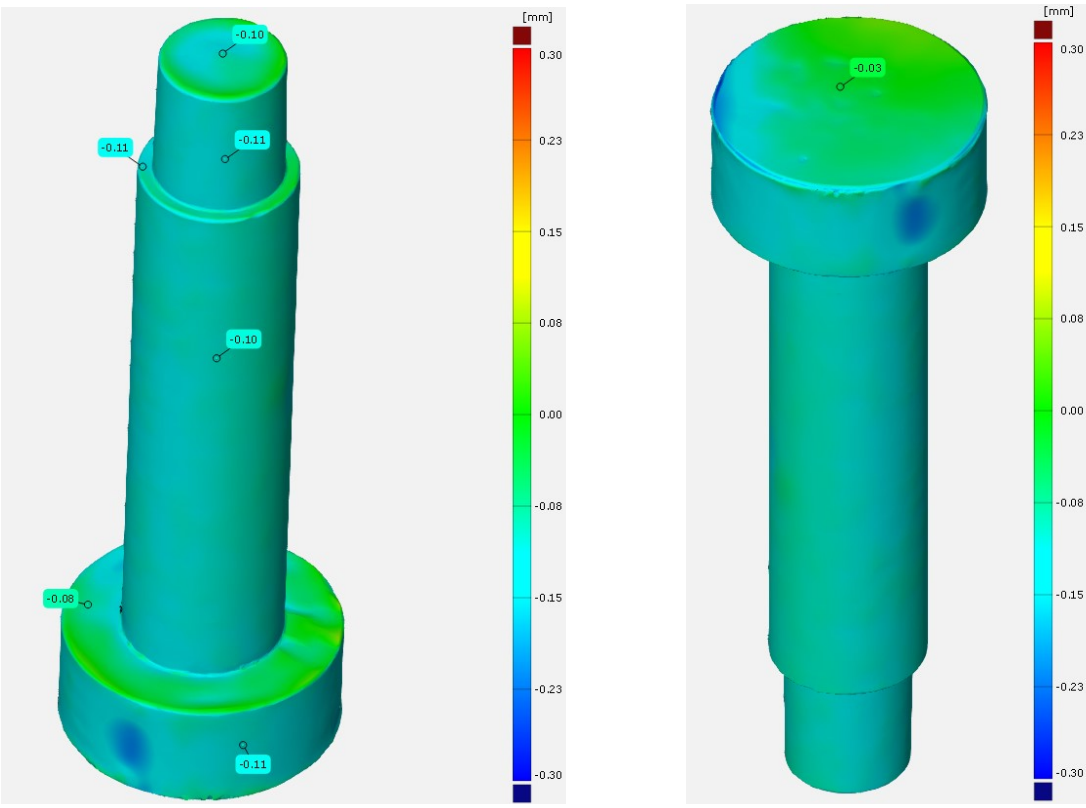
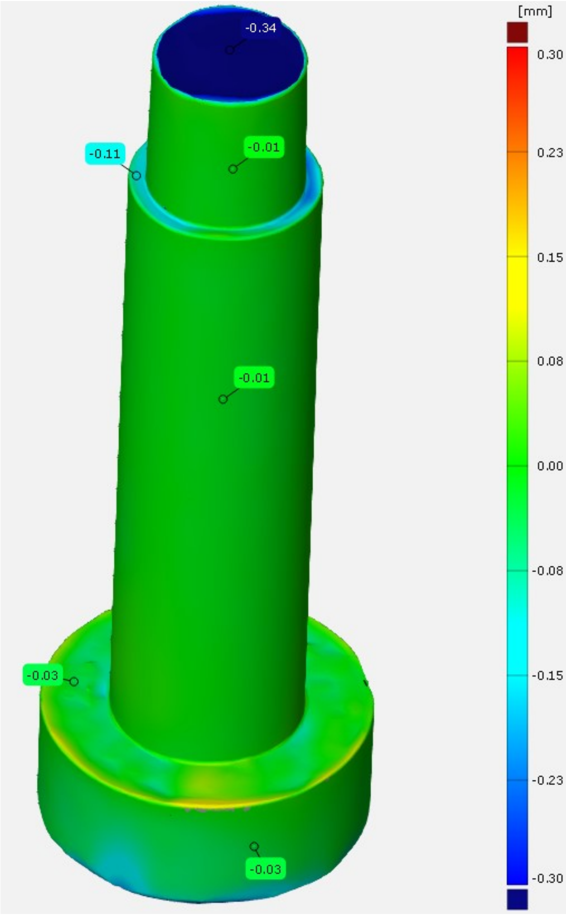


Figure 68. 3D scanned tool steel DMLS insert, slightly better dimensional accuracy than the aluminium DMLS insert, but still significant deviation from nominal dimensions



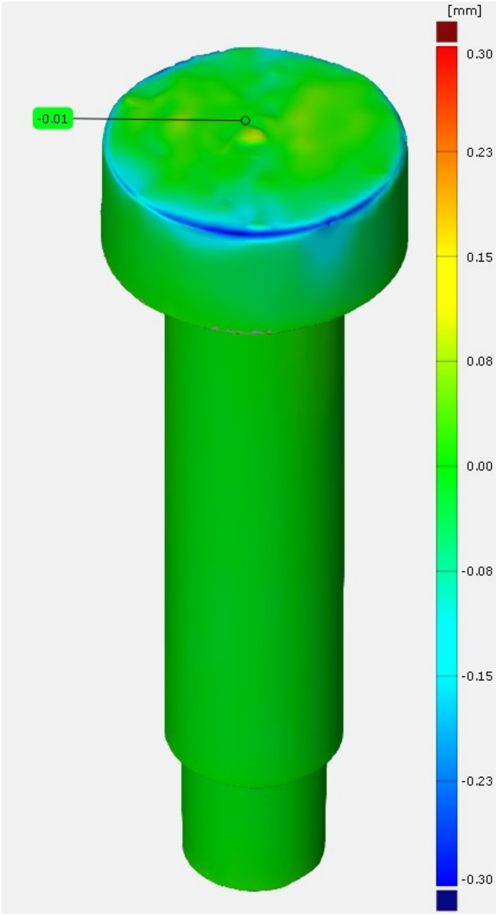


Figure 69. 3D scan of stainless steel DMLS insert, very little deviation from nominal dimensions, except for the top of the part

Further tests with DMLS inserts, with different materials, were not done in this study, due to time constraints.

5.2 Evaluation of the benefits and challenges of utilizing AM IM tools in the PDP

When evaluating the benefits of introducing AM IM tools to make prototypes during the PDP, one of the most significant factors was that would it make the product development process faster? As presented in chapter 4.3, there was three parameters that affected the overall time of producing prototypes by using AM IM tools; the design of the tools, manufacturing of the tools and fitting the tools to the mold. These lead times from the practical implementation of this study are presented in table 4. The lead time for 3D printed prototypes are also included as reference.

Production part			
Tool design	*Tool manufacturing*	*Tool fitting*	*Total*
3 weeks	2 weeks	1 week	6 weeks
Detail design part			
Tool design	*Tool manufacturing*	*Tool fitting*	*Total*
3 weeks	1 week	1 week	5 weeks
3D-printed SL			
-	-	-	1 week
3D printed SLS			
-	-	-	1 week
Variation of existing part			
Tool design	*Tool manufacturing*	*Tool fitting*	*Total*
4 weeks	2 weeks	-	Over 6 weeks

Table 4. Lead times for the different prototypes.

As can be seen from table 4, there is some variation in the lead time for the different prototypes produced with the AM IM tools. The biggest impact on the lead time of the production part, was the design of the AM inserts. It should however be noted, that the mold used for prototyping was designed by the same designer in parallel with designing the inserts. The additive manufacturing of the tools took two weeks for the first inserts, which was exceptional, as it was claimed that the expected delivery time for AM parts from this supplier was one week. Fitting of the tool to the mold platens and finding a suitable slot for a test run took one week. The total of six weeks for getting the first prototypes, is quite a long time, especially compared to the delivery time of 3D printed prototypes which is one week or less. There were however some obstacles present during the process, including designing a new mold instead of using the CMS mold, due to reasons described in chapter 4.1. Also, the longer delivery time for the AM IM tools added to the overall lead time. The practical implementation of the production part for benchmarking, provided valuable insight into the different stages involved in designing, manufacturing and fitting of AM IM tools.

The lead time for designing the inserts for the production part was also three weeks. However, the manufacturing of the AM tools was reduced to one week, whilst the fitting of the inserts to the mold platens was roughly the same as for the production part. The total time of five weeks, indicates that a lead time of five to six weeks can be expected when using the resources similar to the ones used during the practical implementation in this study, despite the difference in complexity of the part. It should be noted that this lead time is based on the experiments where the AM IM tools were manufactured out of plastic resins. Also, the failures of the inserts during the detail design part testing were not included in the lead time datasets, as these failures were determined to be due to a design flaw, not due to the process itself.

For the third case study, the variation of an existing product, the design time was four weeks and the manufacturing time was two weeks. The extension in design time was mainly due to the complexity of the part, which demanded several smaller inserts and slides to be designed. The manufacturing time was two weeks because of ordering issues, which when avoided the time ought to be reduced to one week. As the aluminium AM IM tools could not be used as intended, due to the issues described in chapter 4.3.3, the fitting time and total lead time could not be determined based on this case study.

The lead time analysis for AM IM tools was done based on using the same resources at CM Tools for all three cases, to get reliable data based on a realistic product development scenario at ABB WA, where the tool design and the manufacturing of the AM IM tools would be outsourced. Although the lead times in this study were longer than predicted and suggested by earlier studies, the process could be improved by effectively implementing the design tools described in chapter 4.2 and by reducing the amount of outsourcing.

A relevant fact to point out is that the lead time for manufacturing the AM IM tools were on average the same as 3D printing prototypes, which is significantly faster than manufacturing the inserts by traditional tool manufacturing methods. This shows that time could be saved at this stage of the process, when expecting that the design and fitting times would stay the same regardless of the manufacturing method.

Another goal in this study was to evaluate the benefits of utilizing AM IM tools for producing prototypes for different functions inside the company as well as the learning aspects of utilizing taper integration by outsourcing, as described in chapter 3.1. The focus was on the product development team, but also product managers and the production technology team members were involved. Based on discussions with these three functions, the verdict from the product development team was that the process was still too slow and the quality of the parts were not as good as expected, mainly due to flashing and warpage. The product manager used the prototypes manufactured with AM IM tools to get feedback from customers about the product that was in detail design. The conclusion from this was that prototypes made from the real material and with the final production method can be beneficial when collecting feedback from customers.

As for the production technology team, they saw potential in using prototypes made with AM IM tools for testing assembly equipment however, as the implementation of the aluminium insert was unsuccessful, the benefits of utilization of these prototypes was inconclusive in this study.

The results in this study regarding the utilization of AM IM tools to improve the PDP were promising. As supported by other case studies and shown in this study, AM IM tools are a viable source for different situations in the PDP. There are however clearly some obstacles left, such as the quality of aluminium AM IM tools and cooling of plastic inserts, that needs to be solved before true benefits can be achieved from the wide scale usage of AM IM tools in the PDP.

6 Conclusions and discussion

The purpose of this thesis was to study the benefits of using additively manufactured injection molding tools in the product development process. The practical implementation of the study was done by designing and acquiring a mold base for testing of AM IM tools, choosing three different products in different levels of development; a part that is already in production, a part that was in the detail design phase and a part that was a new variation of an existing production part. Prototypes were made with the AM IM tools designed for these products. The implementation was evaluated out of a technical perspective as well as out of a process perspective. The technical evaluation involved measuring the prototypes with two different methods, with video measurement equipment and with a 3D scanner, functional testing of the prototypes through assembly and visual inspection of the AM IM tools. The process was analyzed in terms of lead time, design methods and resources.

Valuable knowledge about additive manufacturing, injection molding with additively manufactured tools and introducing a new method into the product development process, was obtained during this study. The fundamental understanding of both the injection molding process, tool design and additive manufacturing through literature studies and the professional knowledge found at ABB WA, CM Tools and Proto Labs as well as proof of concept through previous research on utilization of AM IM tools, made the implementation of the study efficient and different materials and parameters could therefore be tested. By starting with a production part, the technical feasibility of the mold and the AM IM tools could be studied. In addition, the impact of different holding pressure profiles could be tested, as the shape of the production part was such that the AM IM tools could be made robust enough to withstand higher pressures. The test results showed that some dimensions could be influenced by changing the holding pressure profile.

The practical implementation of the detail design part provided valuable learnings on what kind of structures should not be designed into plastic AM IM tools. After the reinforcement of the failing AM IM tools, the experiment however showed that a more complicated part than the production part could be produced with AM IM tools. The material used for this implementation, DSM Somos nanotool, also proved to be inferior to the material used in the first implementation, which was Accura Bluestone. Also, the quotation for a traditionally manufactured injection mold from Proto Labs showed that although it could be feasible in some situations, in this case the modifications that would have been necessary to be done to the part to able to manufacture the mold would have had too big of an impact on the intended geometry of the part.

The third practical implementation, was decided to be done with DMLS technology, as the two first test had been carried out with plastic AM IM tools. Aluminium was chosen as material for the inserts, due to its promising properties and to evaluate the feasibility of using aluminium DMLS inserts. The part that was chosen for this implementation was considerably more complex than the two previous parts, and the choice of aluminium for the AM IM tools proved to be a failure. The quality and dimensional accuracy of the aluminium DMLS tools was not high enough to be used for injection molding, without considerable post processing by traditional tool manufacturing methods. Different materials were therefore evaluated, to examine whether DMLS could be utilized for prototyping with AM IM tools without excessive post processing. The results were promising for the DMLS inserts manufactured out of stainless steel. The conclusion was that further tests need to be done to be able to confirm these assumptions. However, these tests were not conducted in this study due to time restrictions.

The processes that were analyzed in this study was the product development process at ABB WA and the process of producing prototypes by utilizing AM IM tools. The study of the product development process at ABB WA, showed that there are clearly product development phases that could benefit from injection molded prototypes. The biggest need for AM IM prototypes was concluded to be able to do standardized functional tests at an early stage of the process, with prototypes made with the correct production method and out of the specified material. Other benefits from utilizing IM AM tools, was better feedback from customers and an improved overall lead time.

By analyzing the process of manufacturing prototypes with AM IM tools, it was concluded that the process contains three phases; design, manufacturing and fitting and test run. The lead time from the first implementation was six weeks, the second implementation was five weeks and the lead time for the third implementation was inconclusive, as the test run failed. The shortest lead time of five weeks, contained three weeks of design, one week of manufacturing and one week of fitting and test run. This lead time was concluded to be realistic, however, with the resources used, the lead time, especially for the design phase, could be improved with better resource management. It should be pointed out that iterations due to change in the geometry of the part can be done considerably faster, as the design phase is shorter.

Further studies that should be done include cooling of plastic IM AM tools, as the cycle times were long and warpage from uneven shrinkage was significant in the prototypes produced during this study, mainly due to insufficient cooling of the tools. Also, metal AM IM tools for prototyping should be tested further, as the tests done in this study did not provide an answer to whether it would be beneficial to implement DMLS IM tools in the PDP. Especially when larger series of 100-1000 parts are to be produced, further research need to be done to evaluate which manufacturing method is the most effective.

As a conclusion, utilizing AM IM tools in the PDP showed promising results and should be considered to be incorporated into the PDP at ABB WA, as an alternative method for producing prototypes. For the most benefit the need for prototypes should be assessed for every project and a plan should be made at the beginning of each new project. If there is a need for standardized testing, then the use of AM IM tools should be considered as an alternative to improve the lead time of the overall PDP. This suggestion is supported by previous research done on the benefits of utilizing additively manufactured injection molding tools to improve the product development process.

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